# ALTERNATIVE FUELS COMPATIBILITY WITH ARMY EQUIPMENT TESTING – IN-LINE MONITORING

**INTERIM REPORT**
**TFLRF No. 422**

by
**Gary B. Bessee**

**U.S. Army TARDEC Fuels and Lubricants Research Facility**
**Southwest Research Institute® (SwRI®)**
**San Antonio, TX**

**for**
**U.S. Army TARDEC**
**Force Projection Technologies**
**Warren, Michigan**

**Contract No. W56HZV-09-C-0100 (WD15)**



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## EXECUTIVE SUMMARY

**Objectives:** The objective of this study was to determine the capabilities of online and inline electronic fuel quality sensors.

**Accomplishments:** This study analyzed particle counters and photometers/turbidimeters using different dust particle size distributions and concentrations and various concentrations of water. It was determined that currently, particle counters provide the best equipment to determine particulate contamination and can provide some guidance if the water concentration is excessive. Particle counters and photometers/turbidimeters best attribute is measuring only water contamination.

**Military Impact:** This study allows the Army to improve the fuel quality of the fuel being dispensed to vehicles and equipment. By improving the fuel quality, mission readiness will be improved and less maintenance and repair will be required due to less water and debris in the fuel.

# FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period December 22, 2010 through February 21, 2012 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-DP/MS110) served as the TARDEC contracting officer's technical representative. Mr. Joel Schmitigal and Mr. David Green of TARDEC served as project technical monitors.

The authors would like to acknowledge the contribution of Messrs. Raymond Lemes and Michael Stuart for conducting the testing, the TFLRF technical support staff along with the administrative and report-processing support provided by Dianna Barrera and Rita Sanchez.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ASTM | American Standards for Testing & Materials |
| CONUS | Continental United States |
| DEF STA | Defense Standard |
| EI | Energy Institute |
| EX | Explosion Proof |
| IP | Institute of Petroleum |
| ISO | International Standards Organization |
| LED | Light Emitting Diode |
| NIST | National Institute of Standards and Technology |
| NTU | Nephelometric Turbidity Unit |
| OCONUS | Outside Continental United States |
| RIO | Red Iron Oxide |
| SRM | Standard Reference Material |
| TARDEC | Tank Automotive Research Development & Engineering Center |
| VCA | Velcon Contaminant Analyzer |

## 1.0 OBJECTIVE

The objective of this task was to conduct in-line/on-line sensor monitoring to determine fuel cleanliness using various electronic sensors.

## 2.0 INTRODUCTION AND BACKGROUND

The two contaminants typically found in aviation fuel are water and dirt. Detecting each contaminant has historically taken separate test methods and instruments to detect and quantify the respective contaminant. The aviation industry is attempting to use electric sensors to measure and quantify each contaminant or ideally, both of them. Water contamination can vary in water droplet size (volume) and the number of droplets (concentration), but typically water will be clear with little or no color. Solid contaminant is not as simple since the solid contamination can consist of rust, fibers, clays, dirt, or other solid materials that can get into the fuel distribution system. Just investigating the clay and dirt types of contamination found in the United States and parts of the Middle East illustrate the variety of particle size distributions, chemical compositions, and varying colors of the solids.[1,2,3] A sample of soil particle size distributions obtained from the Continental United States (CONUS) and Outside the Continental United States (OCONUS) as well as their respective chemical analysis are provided in Table 1 and Table 2.

Table 1. Particle Size Distributions of Soil Samples from CONUS and OCONUS, counts/mL

| Particle Size, µm | 4 | 5 | 6 | 8 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|---|
| **Location** | | | | | | | |
| Ft. McClellan, AL | 1020 | 823 | 694 | 414 | 247 | 83.6 | 36.0 |
| Twenty-nine Palms, CA | 1014 | 588 | 423 | 203 | 120 | 53.7 | 33.4 |
| AC Fine Test Dust | 751 | 579 | 467 | 262 | 156 | 56.0 | 25.4 |
| Saudi Arabia 5 | 609 | 399 | 323 | 197 | 135 | 71.2 | 44.8 |
| Saudi Arabia 2 | 560 | 426 | 359 | 227 | 153 | 67.2 | 34.3 |
| Ft. Hood, TX | 517 | 377 | 309 | 186 | 123 | 57.6 | 32.1 |
| AC Coarse Test Dust | 504 | 353 | 283 | 164 | 103 | 41.4 | 20.3 |
| Ft. Irwin, CA | 332 | 231 | 184 | 110 | 74.2 | 35.4 | 19.6 |
| Ft. Stewart, GA Range 18553 | 154 | 116 | 97.0 | 62.5 | 45.4 | 25.0 | 13.7 |

Table 2. Calculated Oxide Mass Percentages

| Particle Size, µm | $Al_2O_3$ | $SiO_2$ | MgO | CaO | $TiO_2$ | $Fe_2O_3$ | ZrO | BaO |
|---|---|---|---|---|---|---|---|---|
| Location | | | | | | | | |
| Ft. McClellan, AL | 19.8 | 49.6 | --- | 2.8 | 0.5 | 4.9 | --- | --- |
| Twenty-nine Palms, CA | --- | 1.7 | --- | 9.9 | 0.8 | 3.0 | --- | --- |
| AC Fine Test Dust | 24.0 | 61.8 | --- | 1.8 | 0.5 | 4.3 | 0.2 | 0.4 |
| Saudi Arabia 5 | 3.4 | 24.0 | 45.8 | 9.7 | --- | 0.6 | 0.2 | 0.2 |
| Saudi Arabia 2 | 5.3 | 13.5 | --- | 14.8 | 0.2 | 1.6 | 0.1 | --- |
| Ft. Hood, TX | 9.4 | 20.3 | --- | 11.5 | 0.2 | 1.3 | 0.1 | --- |
| AC Coarse Test Dust* | 11-17 | 65-76 | 0.5-1.5 | 3-6 | 0.5-1.0 | 2.5-5.0 | 0.1 | 0.1 |
| Ft. Irwin, CA | 21.5 | 45.4 | --- | 2.8 | 0.5 | 4.7 | 0.2 | 0.4 |
| Ft. Stewart, GA Range 18553 | 21.7 | 59.5 | 1.0 | 1.4 | 1.9 | --- | --- | --- |

**Manufacturers chemical analysis specification*

Based on the elemental and compositional analysis from the referenced documents,[1,2] the soil samples can be grouped as shown in Table 3. All of the samples analyzed during this study are shown in Table 3.

Table 3. Soil Groupings According to Elemental and Compositional Analysis

| Soil Grouping | Sample Location |
|---|---|
| High calcium, no magnesium silicate | Saudi Arabia 1<br>Saudi Arabia 2<br>Ft. Hood, TX South Range<br>Camp Pendleton, CA<br>Ft. Polk, LA |
| Magnesium Silicate | Saudi Arabia 3<br>Saudi Arabia 4<br>Saudi Arabia 5<br>Yuma Proving Grounds, AZ |
| High Silicate | Ft. Stewart, GA<br>Ft. Stewart, GA Air Filter Debris<br>Ft. Stewart, GA Range 18552<br>Ft. Stewart, GA Red Cloud<br>Fr. Irwin, CA<br>Ft. McClellan, AL<br>AC Fine Test Dust<br>AC Coarse Test Dust<br>PTI fine Test Dust<br>PTI Coarse Test Dust |

Figure 1 through Figure 3 illustrate the differences in color for the various test dusts, including ISO 12103-1 A3 Medium Test Dust which is a standard test dust.

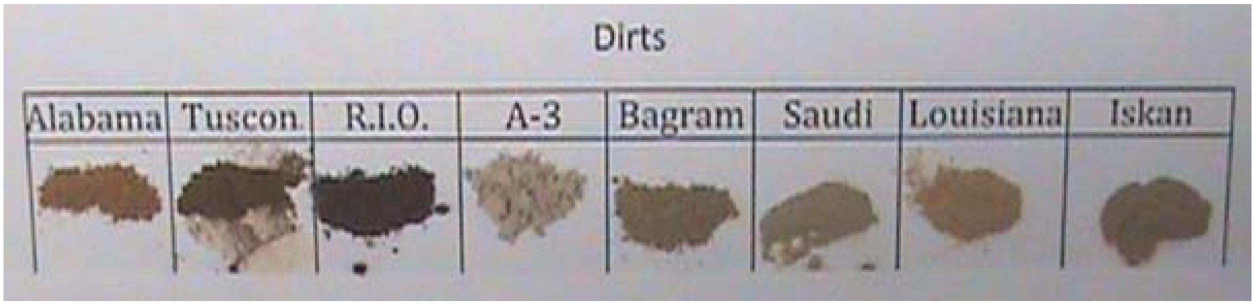



**Figure 1**. Samples of Dirt's from around the World Comparing Color to ISO 12103-1 A3 Medium Test Dust

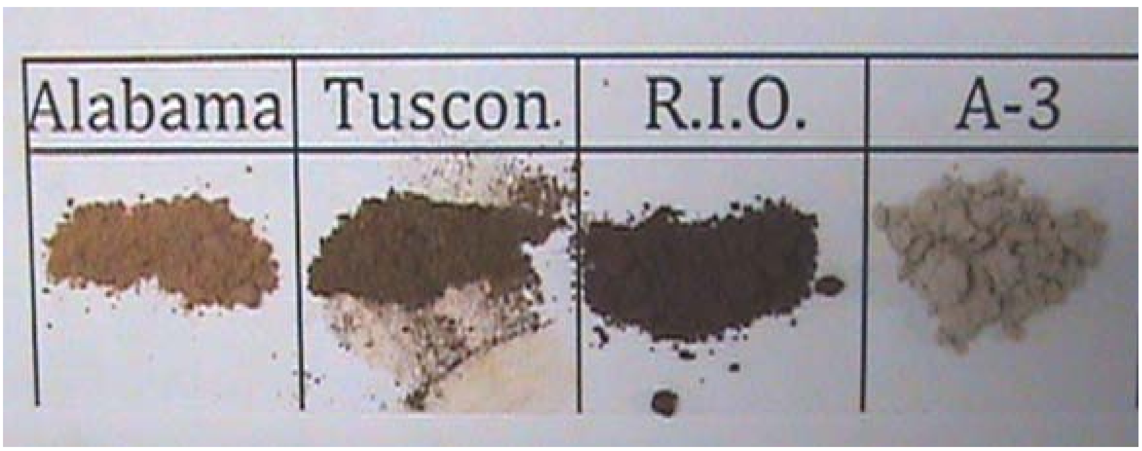



**Figure 2**. Close-Up View of Dirt's from around the World and ISO 12103-1 A3 Medium Test Dust

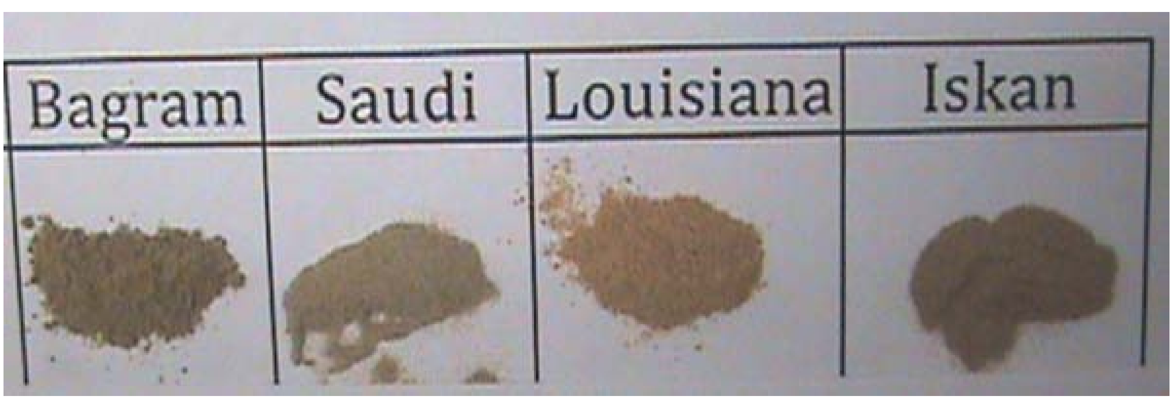



**Figure 3**. Close-Up View of Dirt's from around the World

As illustrated in Table 1 through Table 3 and Figure 1 through Figure 3, soil samples from various parts of CONUS and OCONUS can differ greatly in size, shape, composition and color. This presents a unique challenge to the instrument manufacturers to accurately quantify the amount of solids in fuel.

This information also is important when attempting to correlate between mg/L and particle size distributions. The density of the solids (dirt, clay, fibers, miscellaneous contamination) will vary, as well as the morphology will impact the mass of the contaminant. Also, particle counters are only measuring up to >30-µm (c), so the manufacturer cannot know the distribution of those particles greater than 30- µm (c), so how is the algorithm written for this unknown.

## 3.0 ELECTRONIC SENSORS

The aviation industry has used Aqua-glo and gravimetric measurement techniques to determine the water and particulate contamination levels, respectively, in aviation fuel for decades. The Aqua-glo uses dyed pads that fluoresce as a function of the water content. The gravimetric measurement processes four liters of fuel through weigh membranes to determine the mg/L of solids contamination in the fuel. One issue with determining the mass of the solid contamination is the user does not know if the contamination is a few large particles or several thousand smaller particles that might not cause damage to the hardware. A second issue determining the contamination levels with these techniques is it is time consuming to take the samples so samples are obtained once a day, or week, or month. Therefore, the user is assuming these few samples are representative of potentially large volumes of dispensed fuel.

The aviation fuel industry, both commercial and military, has been investigating the use of either inline or online electronic sensors to determine the cleanliness of fuel. Currently, the Ministry of Defence (MOD) United Kingdom Defense Standard (DEF STAN) 91-91, Issue 7[4] requests particle count data be reported for particle size ranging from 4-µm (c) to 30- µm (c), along with the International Standards Organization (ISO) 4406 cleanliness code[5]. As stated in DEF STAN 91-91, Table 1 – Test Requirements, Note 4, *"It is the Specifications Authority's intention to* *replace Test 1.3 with 1.4 at the earliest opportunity."* Test 1.3 is determining the particulate contamination at the point of manufacture using either IP423[6] or ASTM D5452[7].

The SwRI aviation test facility has the following sensors already installed for evaluating electronic sensors:

- Parker ACM 20 particle counter
- Parker iCount particle counter
- Faudi Jet Guard sensor
- Optec TF-EX turbidity sensor
- Sigrist DualScat EX photometer

TARDEC also requested the Velcon Contamination Analyzer (VCA) be included in this research. Velcon provided two systems for evaluation – an original version hard-plumbed in the fuel line and a portable unit VCA-CV02.

A summary of the instruments and the technology utilized to measure the fuel contamination are provided in Table 4.

Table 4. Respective Electronic Sensor Technologies

| Electronic Type of Sensor | Manufacturer | Technology | Sampling |
|---|---|---|---|
| ACM 20 automatic particle counter | Parker | Light Extinction/ Obscuration | On-line |
| iCount | Parker | Light Extinction/ Obscuration | On-line |
| AFGuard | Faudi | Light Scatter - turbidity | In-line |
| DualScat Ex | Sigrist | Light Scatter - turbidity | In-line |
| TF-16-Ex | Optec | Light Scatter - turbidity | In-line |
| VCA and VCA-CV02 | Velcon | Light Scatter - turbidity | In-line |

Definitions of on-line versus in-line are provided below:

- On-line – On-line samples is defined as a representative sample is obtain from the main flow stream, analyzed, and returned to the main flow or dispensed into a slop (waste) tank.
- In-line – In-line sample is defined as the entire flow stream is passed through the sensor.

A summary of the advantages, disadvantages, and limitations for particle counters and turbidimeters/photometers technology is provided in Table 5 and Table 6.

Table 5. Advantages, Disadvantages, and Limitations for Particle Counters

| Advantages | Disadvantages | Limitations |
|---|---|---|
| Light obscuration gives good correlated data in the form of particle numbers and sizes. | Side-stream format requires representative sampling add-on. | Currently, the industry cannot differentiate between particulate and water. Large number of greater than 30-µm (c) particles may indicate water presence |
| Particle counting is a mature technology that has been utilized in the hydraulic industry for decades. | Does not differentiate between contaminant types indirectly e.g., dirt and water, or other contaminants. (skewed distribution data can infer presence of water droplets) | Current technology can only measure as low as 4-µm (c) – ISO 11171[8, 9] |
| Industry standards are available for use and calibration | Calibration probably requires removal from the refuelling vehicle and calibrated in-house or at an outside laboratory. | Requires a constant flow rate as output is reported as counts/millilitre (mL) and the volume is critical to the accuracy of the results. |
| Good industry defined traceability. | | Particle counting results cannot be correlated to gravimetric results |
| Small, compact units are available. | | Electrical or battery requirements |
| Flexible interfacing | | |
| Industry recognized standard cleanliness codes – ISO 4406 | | |
| Continuous real-time use | | |

Table 6. Advantages, Disadvantages, and Limitations for Photometers/Turbidimeters

| Advantages | Disadvantages | Limitations |
|---|---|---|
| Full flow monitoring possible through the actual sensing zone | Difficult to differentiate well between contaminants, e.g., dirt , water, or other contaminants | Large sensor unit requires major changes to existing pipework – in some cases may not be possible |
| Flexible interfacing | Droplet size can influence the results | Electrical requirements |
| Continuous real-time use | Specific industry protocols require the development of a sensor specific for aviation fuel | |
| Seems to have good correlations determining free water content | Requires algorithm to convert NTU values to ppm | |
| | No industry standards for reference for calibration | |
| | Requires turbulent flow (VCA) | |

## 4.0 TEST PLAN

The test plan for evaluating the selected electronic sensors used the basic concepts used in development of Energy Institute (EI) 1598 – Design, functional requirements and laboratory testing protocols for electronic sensors to monitor free water and/or particulate matter in aviation fuel. This test plan only addressed if the sensors could differentiate between the various types and quantities of test dusts and water and the combination of water and dirt. The water distribution was generated using the centrifugal pump specified in EI 1581. The testing was performed at a high flow rate to ensure turbulent flow and no filtration devices were used between the contaminant injection and the electronic sensors. The test protocol for evaluating the various sensors is provide below:

1. Operate the system at approximately 105.7 gpm (400 lpm) in a single pass flow loop (contaminant is removed after electronic sensors)
2. Using clean, dry, Jet A, obtain baseline data for 30 minutes
3. Upon completion of baseline, obtain data when injecting ISO 12103-1 A1 ultrafine test dust at approximately 1 mg/L, 0.5 mg/L, and 0.25 mg/L
4. Upon completion of ISO 12103-1 A1 ultrafine test dust evaluation, perform the same analysis using ISO 12103-1 A2 fine test dust
5. Upon completion of the ISO 12103-1 A2 fine test dust evaluation, perform same analysis using ISO 12103-1 A3 medium test dust
6. Upon completion of ISO 12103-1 A3 medium test dust evaluation, perform same analysis using Red Iron Oxide (RIO)
7. Upon completion of dirt tests, verify fuel is dry (Aqua-glo)
8. Obtain electronic sensor data using water contamination at approximately 5, 10, 20, and 40 ppm. Verify water contamination levels using Aqua-glo (both Gammon and D2 readers)
9. Upon completion of water tests, test 0.25 mg/L RIO and 5 ppm water

Various test dust distributions were selected for evaluating these electronic sensors as they have different particle size distributions, different chemical structure, and color. Table 7 provides a brief description of each solid contaminant.

Table 7. Various Test Dust Description

| Test Dust | Particle size range, µm (c) | Chemical Description | Color |
|---|---|---|---|
| ISO 12103-1 A1 Ultrafine Test Dust | 0-10 | Quartz, clay, small amounts of carbonate | Quartz is clear, colorless |
| ISO 12103-1 A1 Ultrafine Test Dust | 0-120 | Quartz, clay, small amounts of carbonate | Quartz is clear, colorless |
| ISO 12103-1 A1 Ultrafine Test Dust | 5-120 | Quartz, clay, small amounts of carbonate | Quartz is clear, colorless |
| Red Iron Oxide | 0-10 | Hematite | Red |

All sensors were calibrated by the manufacturer before use per ISO 11171 for particle counters or by the manufacturer’s internal methods for photometers, light scatter devices, and turbidimeters.

## 5.0 TEST RESULTS

Representative data from each of the electronic sensors evaluated during this study are provided below and are also organized into particle counter technology and photometers/turbidimeters. Since the Army specifically requested evaluation of the Velcon VCA and VCA-CV02, those results are presented separately.

### 5.1 PARTICLE COUNTERS

The Parker ACM 20 and the Parker iCount particle counter technologies, Figure 4, were evaluated per the test plan described in Section 4.0. The Parker ACM 20 provides the user with particle counts (counts/mL) for selected channels, as well as the corresponding ISO 4406 cleanliness code. There is additional information available such as volume distribution, but that data will not be presented in this report. The Parker iCount reports the data as ISO 4406 cleanliness codes and as go/no go indicators on the instrument for the field operators.


**Figure 4**. Parker iCount and Parker ACM 20 Parker Counters

Figure 5 presents the Parker ACM 20 particle count data for the concentration of 0.25 mg/L, 0.5 mg/L, and 1 mg/L using ISO 12103-1 A3 medium test dust. As shown in Figure 5, the particle counts are approximately half as the concentration is reduced by half. To determine if these values are realistic, NIST provides particle data for calibration values using Standard Reference Material (SRM) 2806[8] medium test dust. The calibration curve shown in Figure 5 provides comparison of the calibration data against the Parker ACM 20 values. These values are very close and demonstrate the flow system and counters are operating properly.

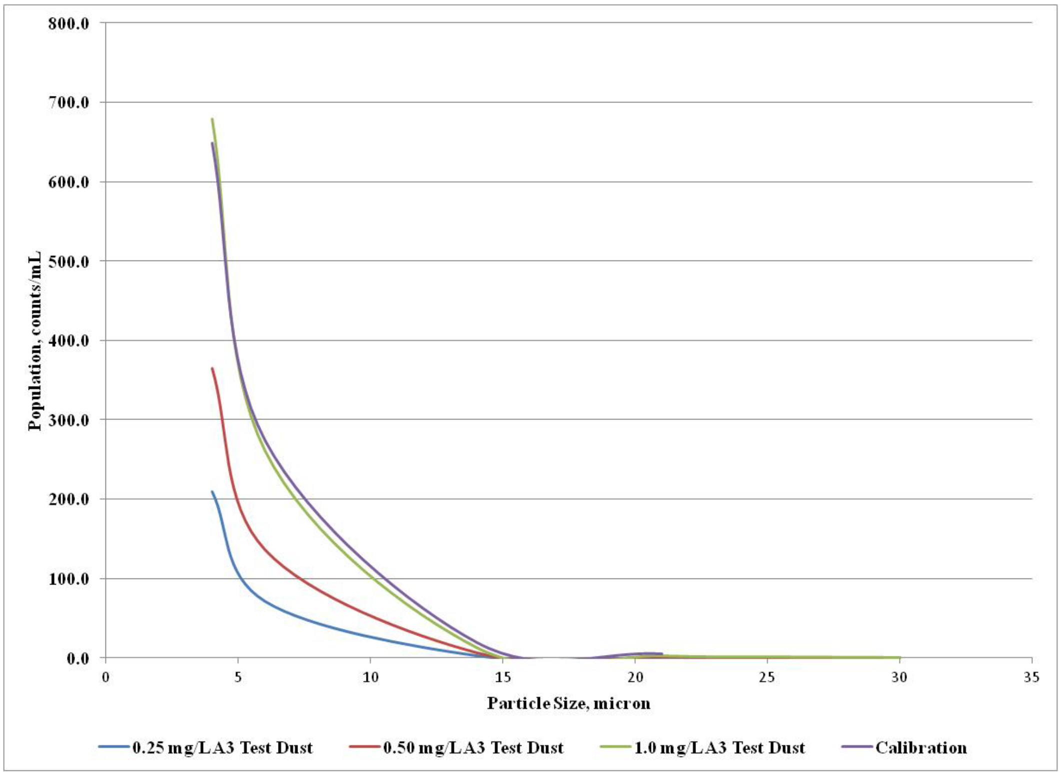



**Figure 5**. Particle Size Distribution of Various Test Dusts

Figure 6 presents Parker ACM particle counting data for 1 mg/L of the various test dusts. This data illustrates the particle counter can differentiate between the various distribution and color (RIO) of the test dusts. Since the Parker ACM 20 and Parker iCount use light extinction to measure the particles, colored bodies (different colored particles) do not affect the output. It is noted that although the ISO 12103-1 A1 ultrafine test dust and red iron oxide (RIO) both have general particle size distributions from 0-10μm (c), the distributions are significantly different with the RIO having significantly more smaller particles.

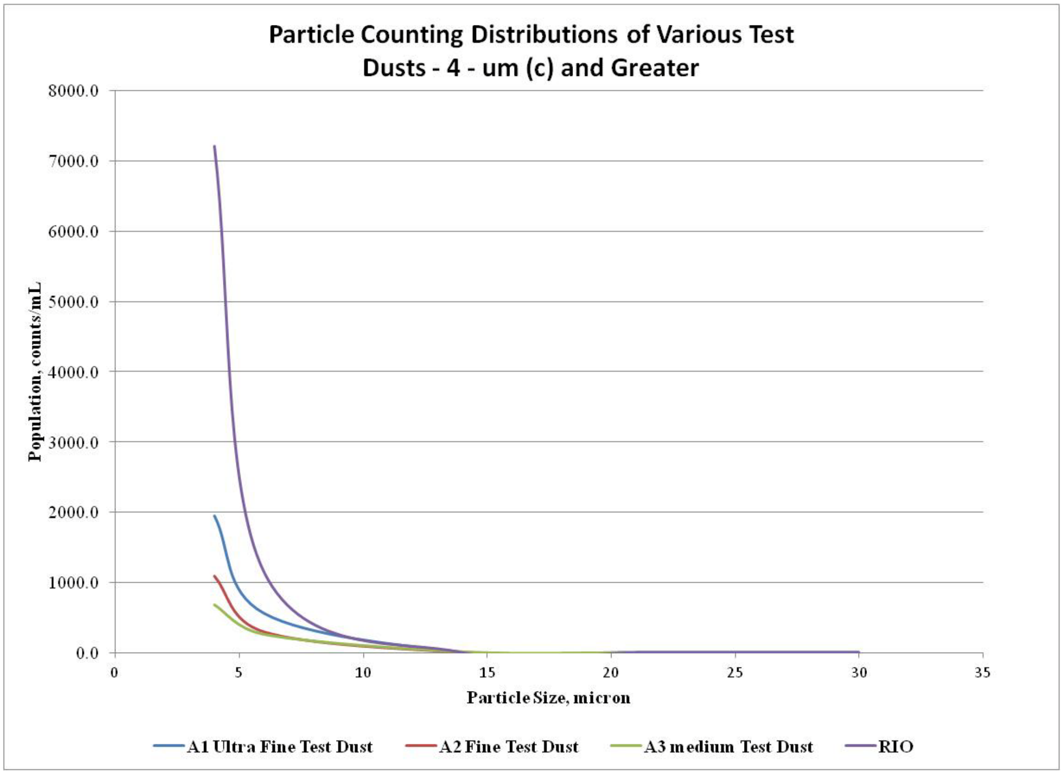



**Figure 6**. Particle Count Distributions of Various Test Dusts – 4-μm (c) and Greater

The Parker ACM 20 was also challenged with various concentrations of water as shown in Figure 7. The water droplet distributions track with the increase in concentration. Although the water droplet distributions are close to linear as a function of water concentration, all electronic sensors will be measuring the fuel cleanliness levels after the filtration process. Therefore, the water droplet distributions will be significantly different. Those distributions will be reported in the JP-8+100 portion of this Work Directive.[11]

The final challenge consisted of dirt and water to determine if the sensor could differentiate between the two contaminants, Figure 8. The bar chart presents the measured and theoretical results based upon approximately 0.25 mg/L RIO and 5 ppm water. The measured results are slightly lower than the theoretical results but within measurement error. This topic will be discussed further in this report.

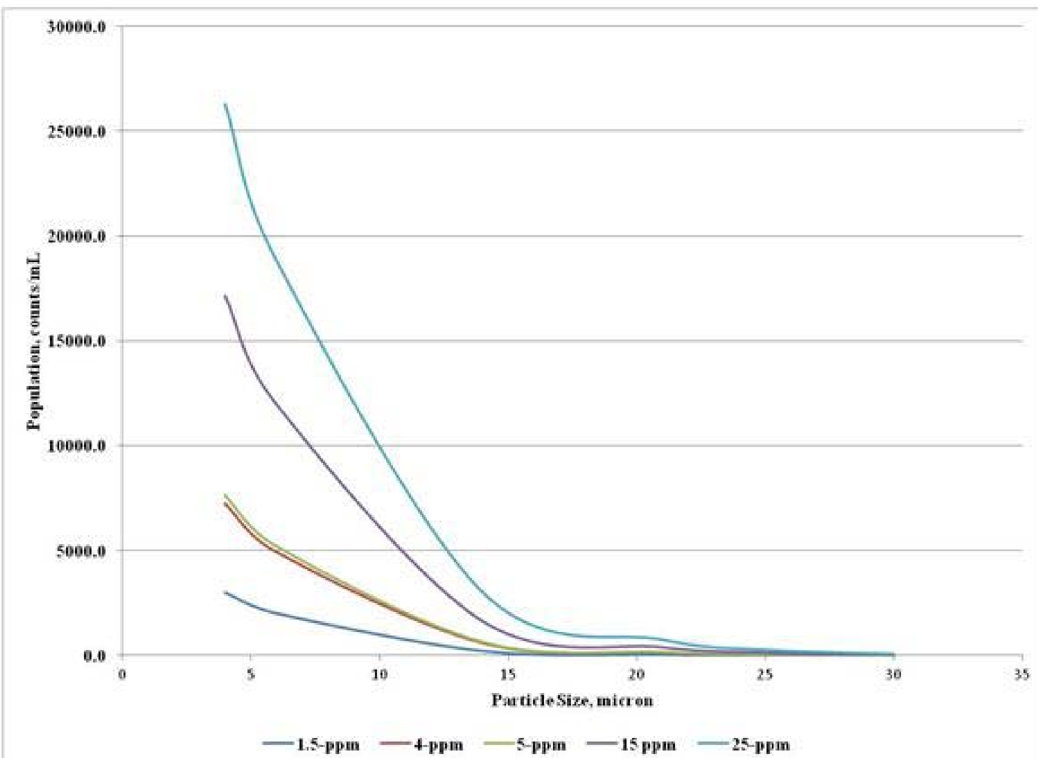



**Figure 7**. Parker ACM Particle Count Results when Challenged with Various Concentrations of Water

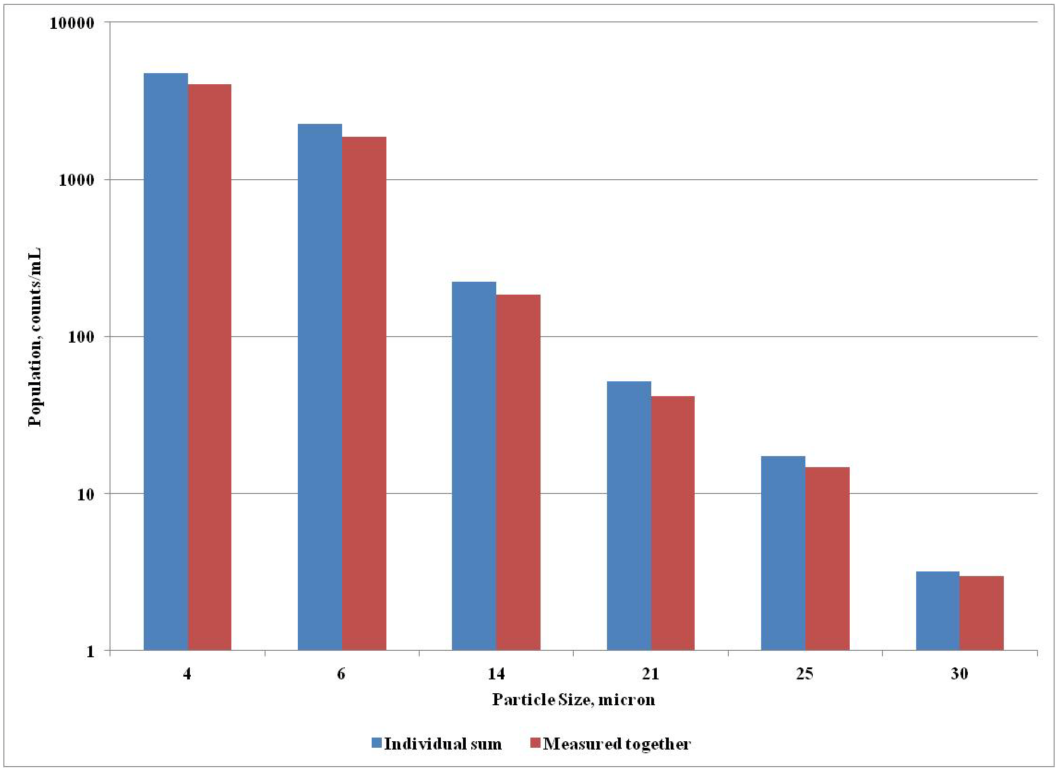



**Figure 8**. Parker ACM Particle Count Results when Challenged with Dirt and Water

The Parker iCount uses the sample particle count principles as the Parker ACM 20 but was designed to provide the user with a lower cost, go/no go device. The output is based on ISO 4406 cleanliness codes (4-, 6-, and 14-µm (c)) and the LED lights are color coded to indicate good fuel (green), approaching the ISO 4406 cleanliness limits (flashing green), and red (exceeds the ISO 4406 cleanliness limits). Parker can set the limits to meet the user's requirements. The minimum ISO code set for the iCount for these evaluation was 7, as that only is measuring less than 1.3 counts/mL. Representative data for the Parker iCount is provided in Table 9, with the remaining data provided in Appendix A.

The Parker iCount data using ISO 12103-1 A3 medium test dust at 1 mg/L is provided in Figure 9. The data output for this sensor is stable and consistent. The noise for the 14-µm (c) data is because of the limit of ISO Code 7 for the instrument. As with the Parker ACM 20, Figure 9 is important as there is available reference data for comparison. Although the data is stable and consistent, the ISO 4406 codes are lower than measured with the Parker ACM 20 than as calculated based on NIST data. The NIST data for ISO 12103-1 A3 medium test dust would be 18/17/13. The Parker ACM 20 ISO 4406 cleanliness codes averaged 17/16/11. The Parker iCount is averaging an ISO 4406 cleanliness code of 17/11/---. The variability of one ISO code is realistic. However, it appears this instrument may have issues measuring larger particles since the 4-µm (c) results are in line with the NIST and Parker ACM 20 instrument. This issue could be calibration or a function of the flow rate used through the sensor. For these evaluations, 100 mL/minute was used which was higher than the manufacturer recommended flow rate.

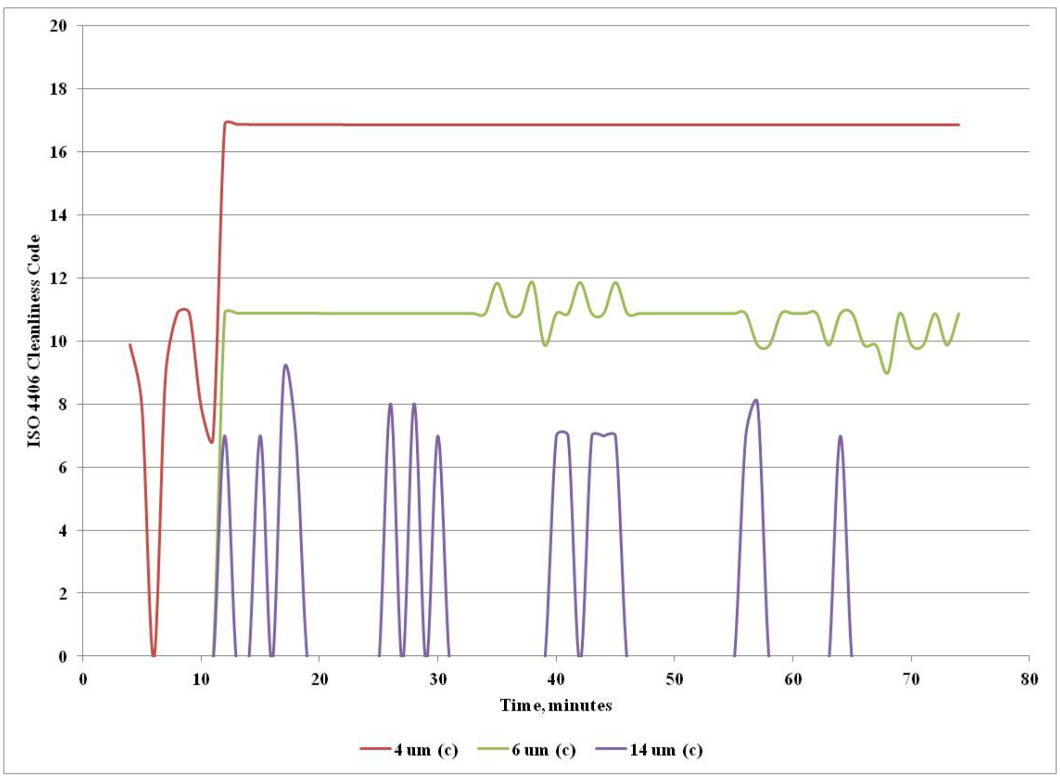



**Figure 9**. Parker iCount Results Measuring ISO 12103-1 A3 Medium Test Dust at a Concentration of 1 mg/L

Figure 10 presents the ISO 4406 cleanliness code data using RIO at 1 mg/L. One would expect high ISO code values for the 4- and 6-µm (c) results and less than 7 for the 14- µm (c) data since the RIO particle size distribution is 0-10 µm (c). Based upon the Parker ACM 20 results, the ISO cleanliness code should be 20/17/8. As with the ISO 12103-1 A3 results, the 4- µm (c) results look realistic, but the 6- µm (c) and higher are lower than would be expected.

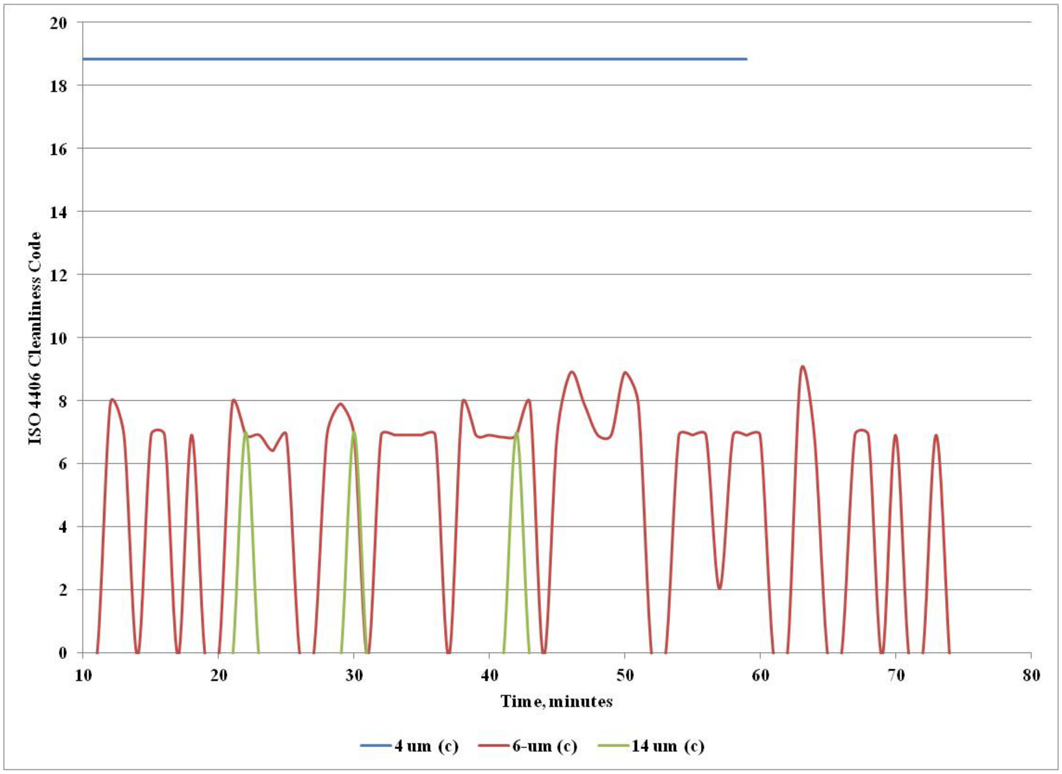



**Figure 10**. Parker iCount Results Measuring Red Iron Oxide (RIO) Test Dust at a Concentration of 1 mg/L

The Parker iCount was challenged with various concentrations of water, Figure 11. The iCount was able to differentiate between the different concentrations and had similar results when challenged with a slight change in the water concentration. Based upon the Parker ACM 20 particle results, the ISO 4406 Cleanliness Codes should be as shown in Table 8. Again there is variability between the two instruments, but the Parker iCount does have the step changes when the water challenges is increased.

The remaining analysis for the various dirt concentrations and test dusts, and water challenges are provided in Appendix A.

Table 8. ISO 4406 Cleanliness Codes as a Function of Water Content

| Measured Water Concentration, ppm | Parker ACM 20 4-µm (c) | Parker ACM 20 6-µm (c) | Parker ACM 20 14-µm (c) | Parker iCount 4-µm (c) | Parker iCount 6-µm (c) | Parker iCount 14-µm (c) |
|---|---|---|---|---|---|---|
| 1.5 | 19 | 18 | 15 | 19 | 15 | 9 |
| 4 | 20 | 19 | 16 | 21 | 17 | 11 |
| 5 | 20 | 20 | 16 | 21 | 17 | 11 |
| 15 | 21 | 21 | 18 | 30 | 19 | 13 |

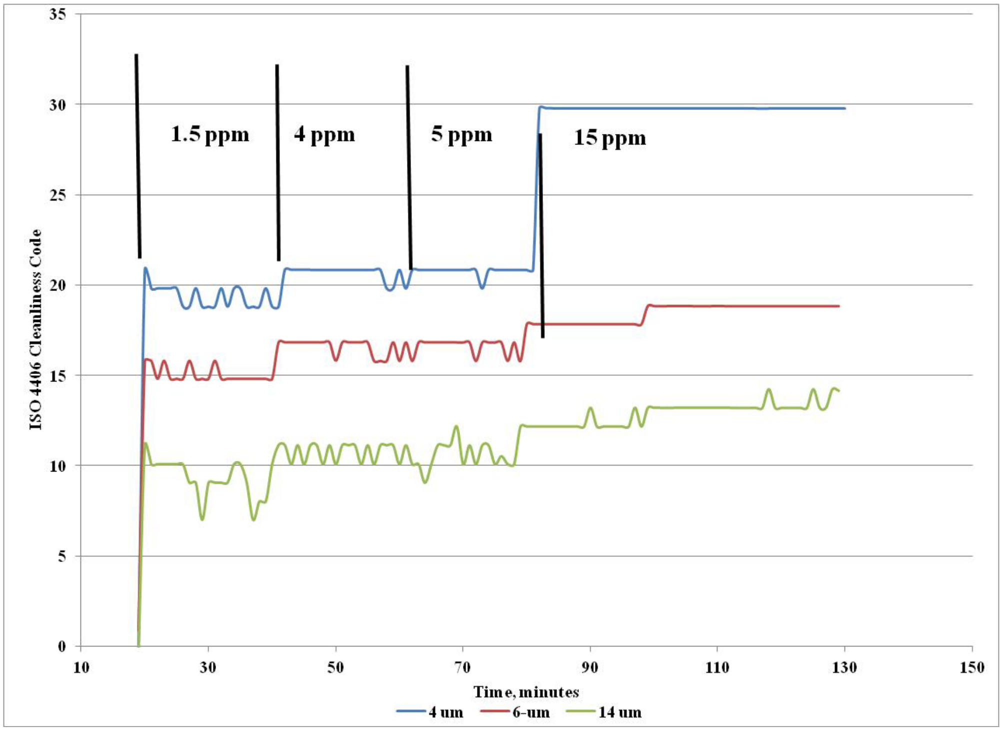



**Figure 11**. Parker iCount ISO 4406 Cleanliness Code Results when Challenged with Various Water Concentrations

## 5.2 VELCON CONTAMINANT ANALYZER (VCA AND VCA-CV02)

The Velcon VCA, Figure 12 was evaluated using the same protocol as was performed using the particle counting technology. The VCA analyzes the data and calculates the gravimetric level and water content based on their own algorithms. A summary of the gravimetric results are shown in Figure 13. As illustrated in Figure 13, the VCA obtained different results based upon the particle size and color of the contaminant. At both the 0.25 mg/L and 0.5 mg/L concentrations using ISO 12103-1 A1 ultrafine test dust, the VCA did not differentiate between these concentration which are at and almost twice the solids limit per EI 1581[12] (0.26 mg/L), respectively.


**Figure 12**. Velcon VCA

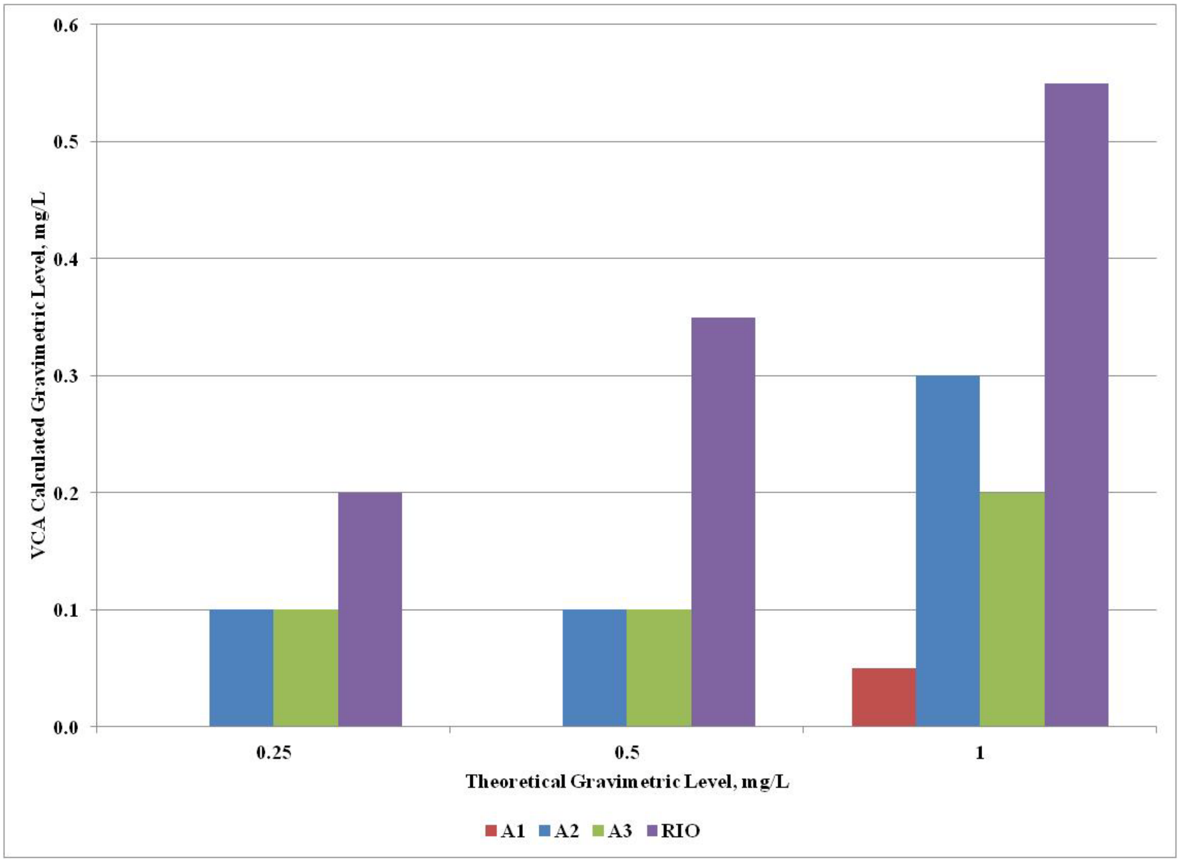



**Figure 13**. Summary of VCA Dirt Challenges Results

The water challenge was evaluated during an EI 1581 evaluation before the unit was required to be returned to Velcon. The water contents measured by Aqua-glo are compared to the VCA water results, Figure 14. The instrument did not correlate well to the Aqua-glo measurements.

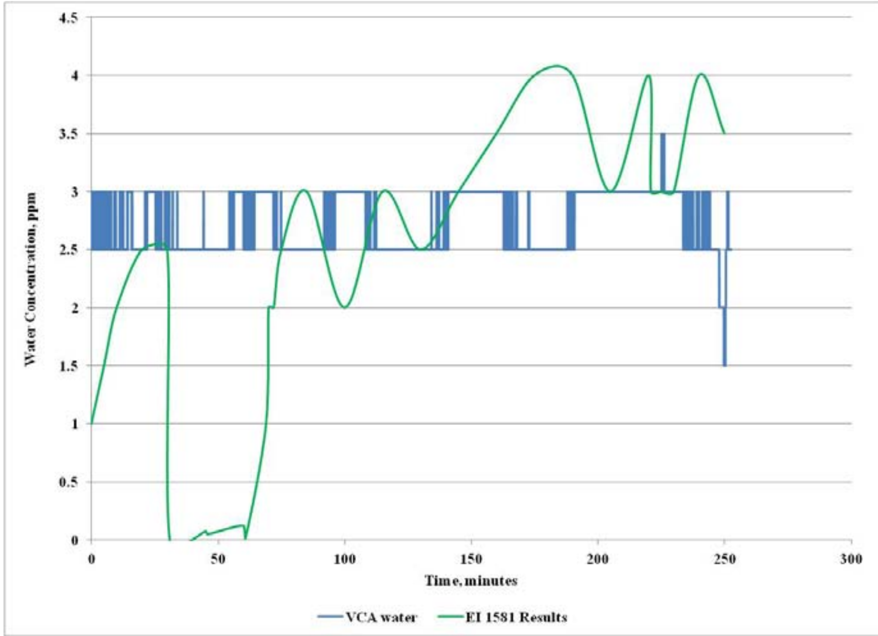



**Figure 14**. VCA Water Content as Measured during an EI 1581 5th Edition Evaluation

Velcon provided a second VCA unit, VCA-CV02, a potable unit, for evaluation which they and TARDEC witnessed. The portable unit is shown in Figure 15.

**Figure 15**. Velcon VCA-CV02 Portable Unit

It is noted that the verification gravimetric results for all of the evaluations on the VCA-CV02 were lower than the theoretical results. The data for the 0.25 mg/L dirt challenges (excluding RIO) are shown in Figure 16 through Figure 18.

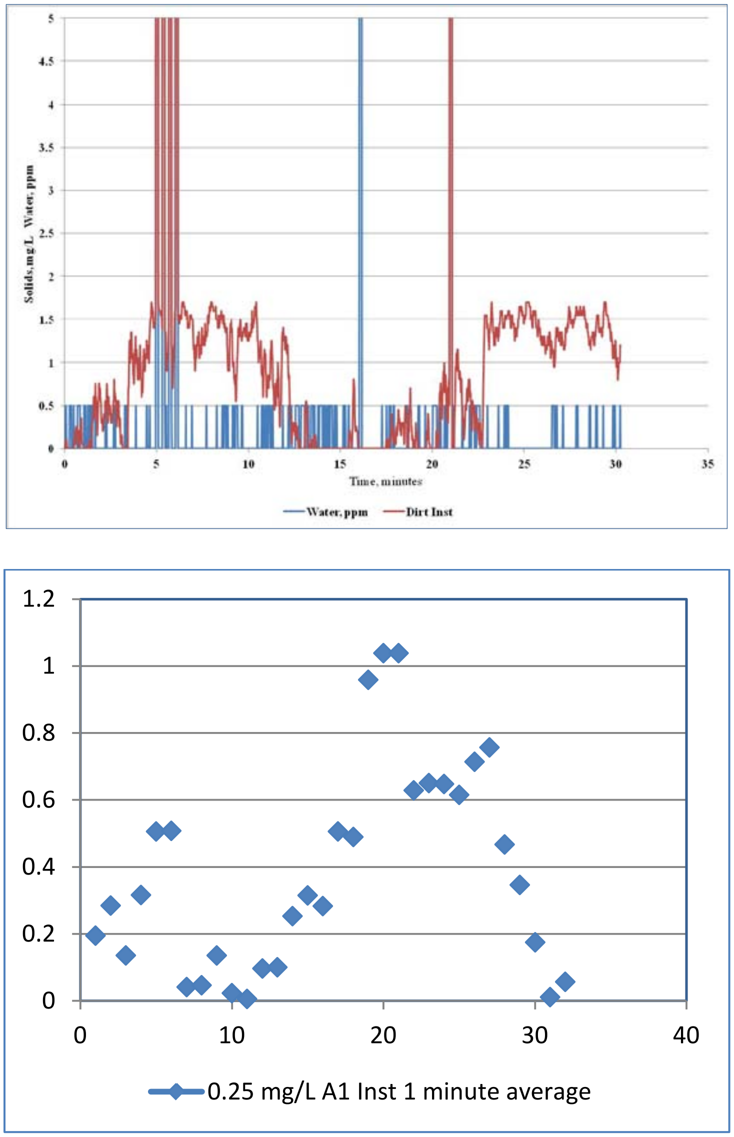
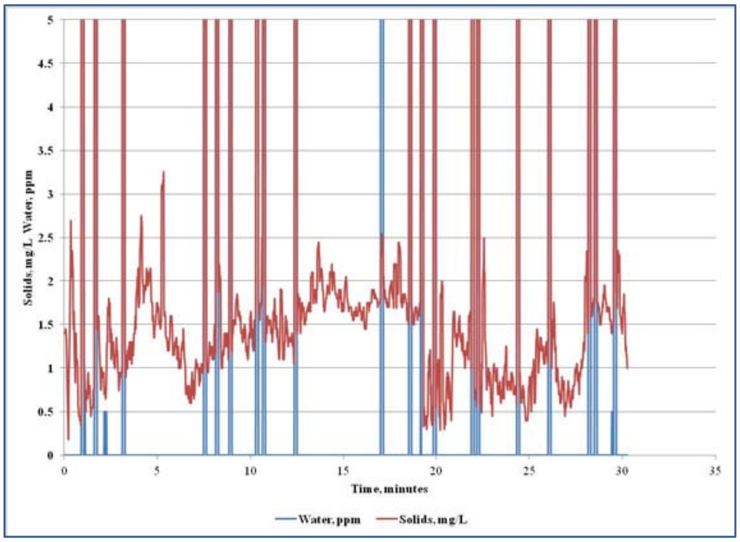



**Figure 16**. VCA-CV02 Results Challenged with 0.25 mg/L
ISO 12103-1 A1 Ultrafine Test Dust – Raw Data and 1 Minute Average



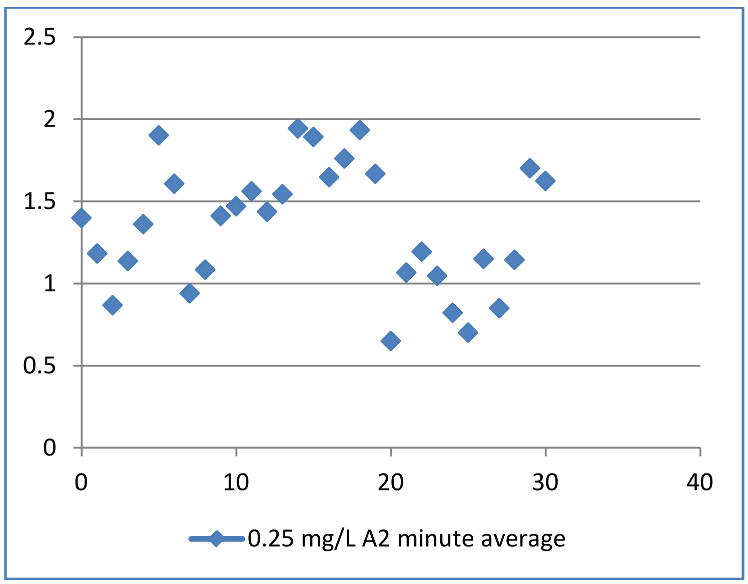
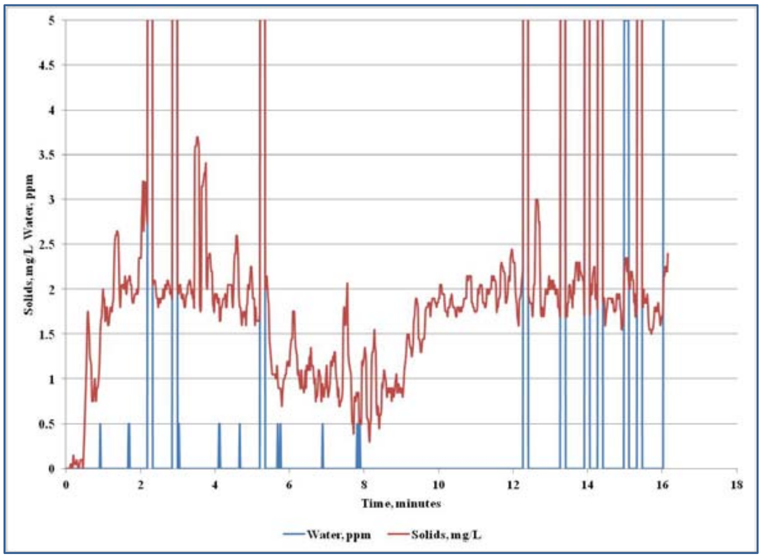




**Figure 17**. VCA-CV02 Results Challenged with 0.25 mg/L ISO 12103-1 A2 Fine Test Dust– Raw Data and 1 Minute Average



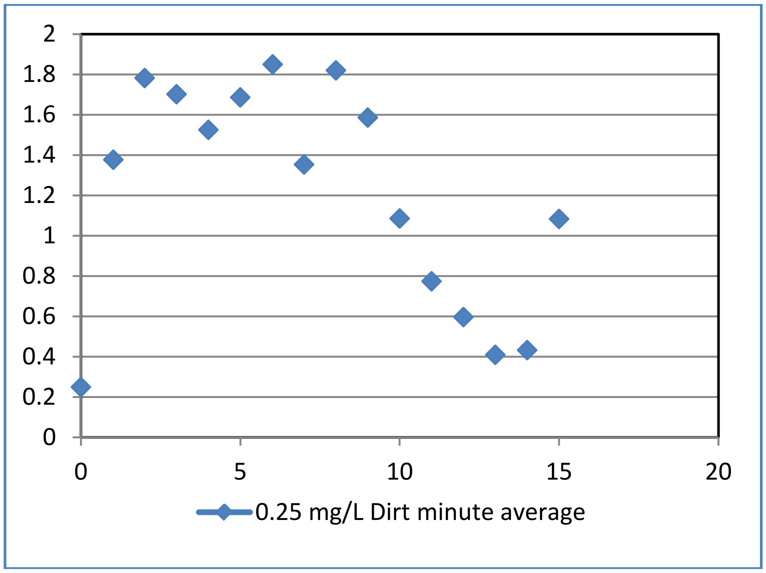




**Figure 18**. VCA-CV02 Results Challenged with 0.25 mg/L ISO 12103-1 A3 Medium Test Dust– Raw Data and 1 Minute Average

As shown in Figure 19, the particle count data was stable and not as erratic as shown in the VCA data. Also, no water was added during these evaluations and the Aqua-glo was less than 1 ppm water. This is important in the algorithm as compared to the original VCA, however, comparing Figure 16 through Figure 18, the results vary as a function of the particle size distribution.

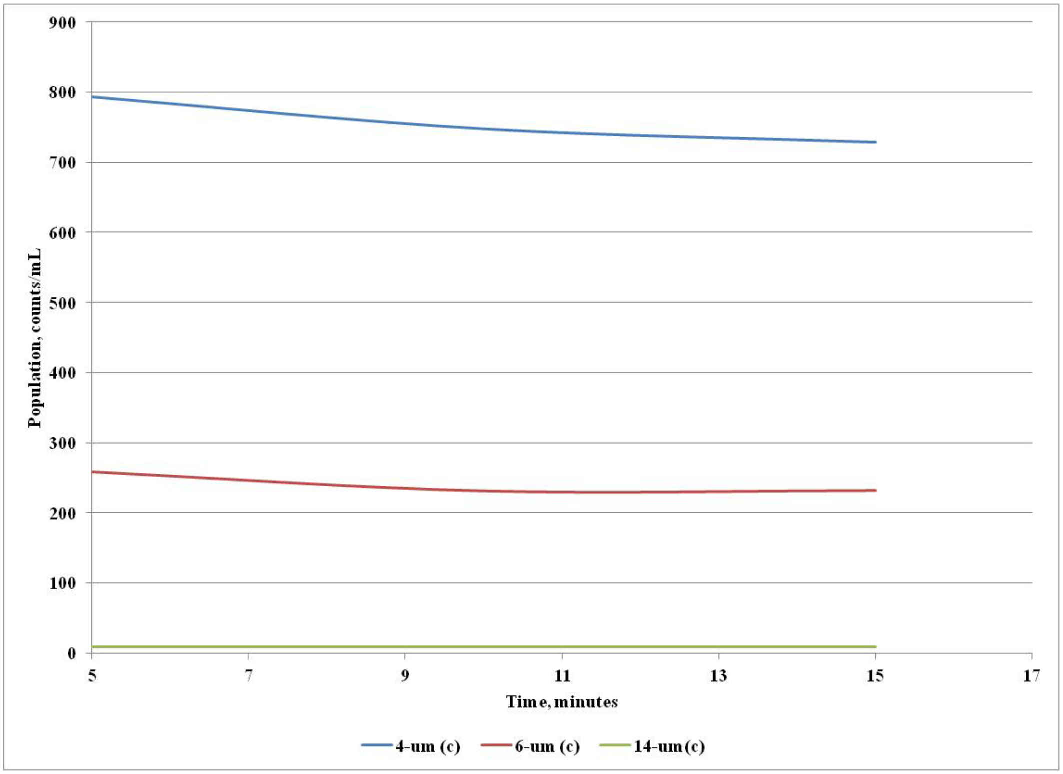



**Figure 19**. Parker ACM 20 Particle Analysis for 0.25 mg/L ISO 12103-1 A3 Medium Test Dust Results as Performed During VCA-CV02 Evaluation

Figure 20 presents the reduced data for 1 mg/L of red iron oxide with no water addition. As with the VCA, colored bodies such as red iron oxide shrew the results higher than the actual or theoretical values.

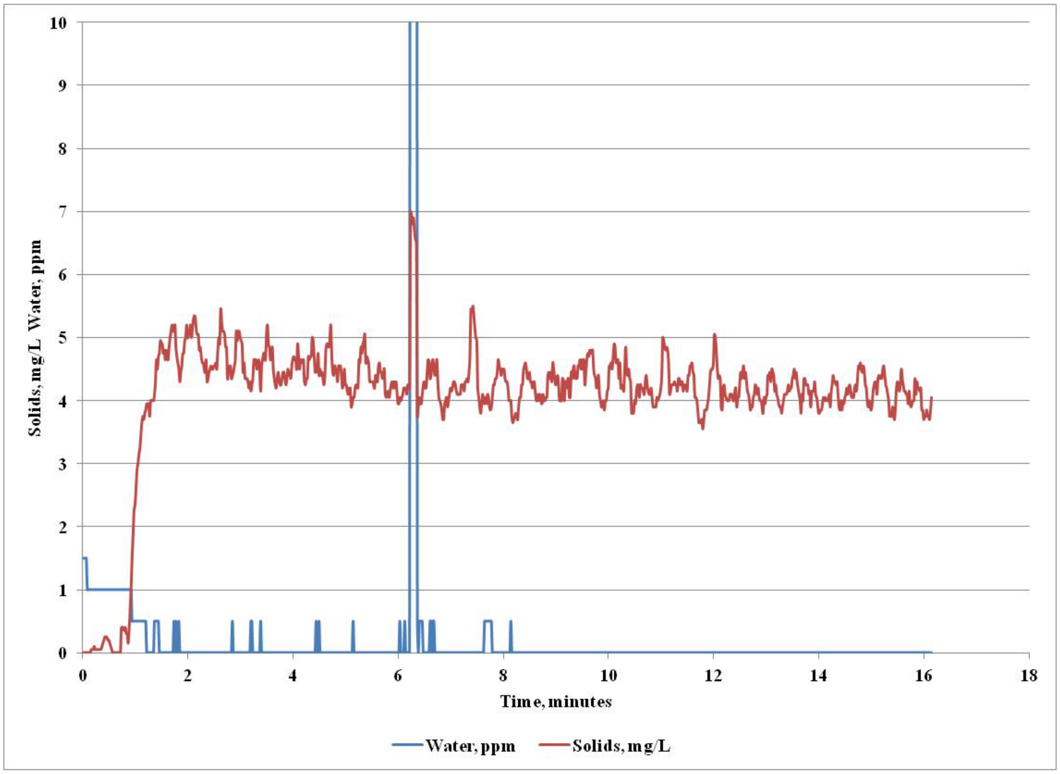



**Figure 20**. VCA-CV02 Challenged with 1 mg/L RIO and No Water

Figure 21 illustrates the results challenging the VCA-CV02 with 0.25 mg/L red iron oxide and 5 ppm of water. There is still a lot of noise but the water content is close to the measured value of 5 ppm for this evaluation.

The water results are substantiated in Figure 22, which challenged the VCA-CV02 with only 5 ppm water. Additional and similar results are provided in Appendix B. Eliminating the spikes, the water content is very close to the target value. However, in both Figure 21 and Figure 22, the results are very similar even with the RIO added in Figure 21.

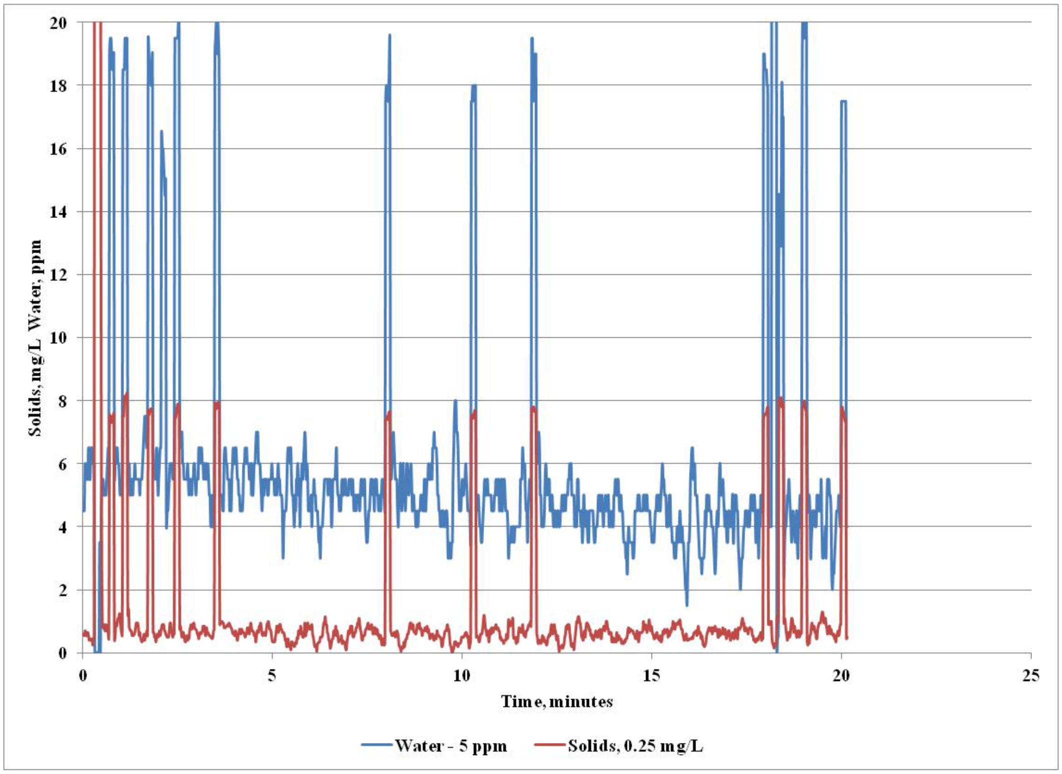



**Figure 21**. VCA-CV02 Challenged with 1 mg/L RIO and 5 ppm Water

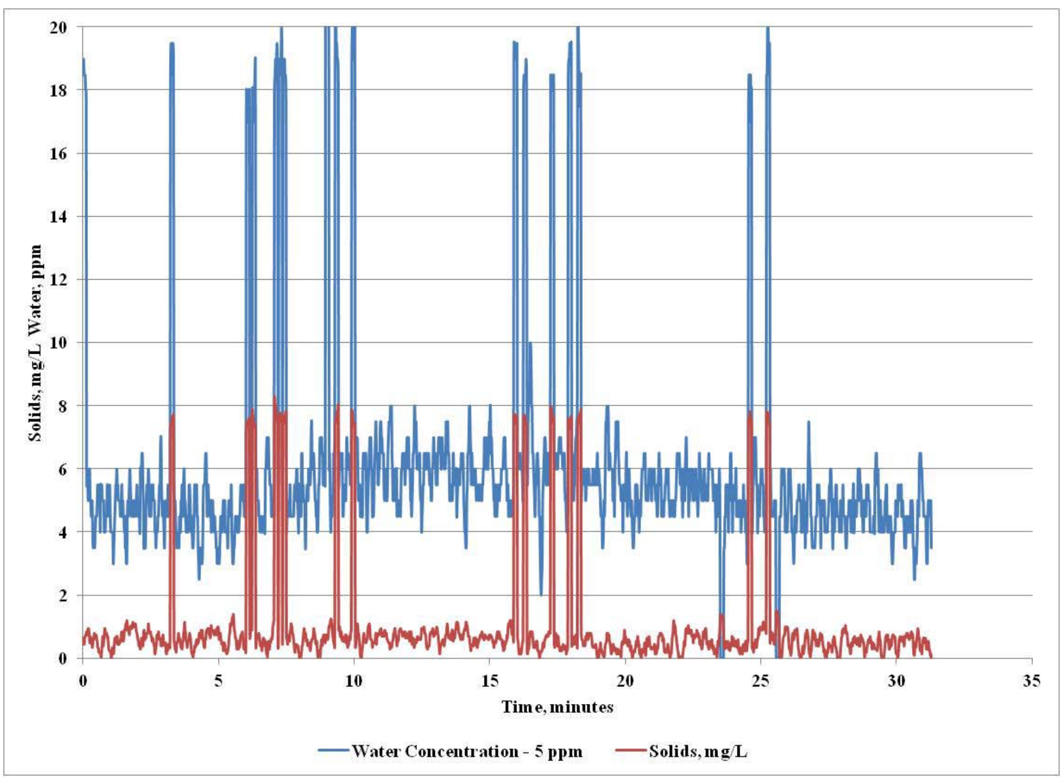



**Figure 22**. VCA-CV02 Challenged with 5 ppm Water

## 5.3 PHOTOMETERS AND TURBIDIMETERS

Additional electronic sensors were evaluated during this study:

- Sigrist DualScat EX photometer, Figure 23
- Faudi Jet Guard sensor, Figure 24
- Optec TF-EX turbidity sensor, Figure 25

**Figure 23**. Sigrist DualScat EX Photometer

**Figure 24**. Faudi Jet Guard


**Figure 25**. Optec TF-EX Turbidity Sensor

The Sigrist DualScat photometer was used in this study as it provides only the raw output, so we could see how the dirt, water, and dirt/water challenges impacted the raw signal. This electronic sensor technology is used in the beer and wine industry. The Sigrist DualScat measures the signal at 25º and 90º. The various photometer and turbidimeter manufacturers use similar technology but may use different angles to develop their algorithm. Examples of the raw data generated by the Sigrist DualScat are shown in Figure 26 and Figure 27.

Figure 26 illustrates the change in response of the 25º signal as a function of water. The initial increase in signal at 35 is the initial introduction of water. As the water challenge is tuned to the proper concentration of 5 ppm, the instrument detects the increases in the water challenge to 10 ppm, 15 ppm, 20 ppm, and 30 ppm.

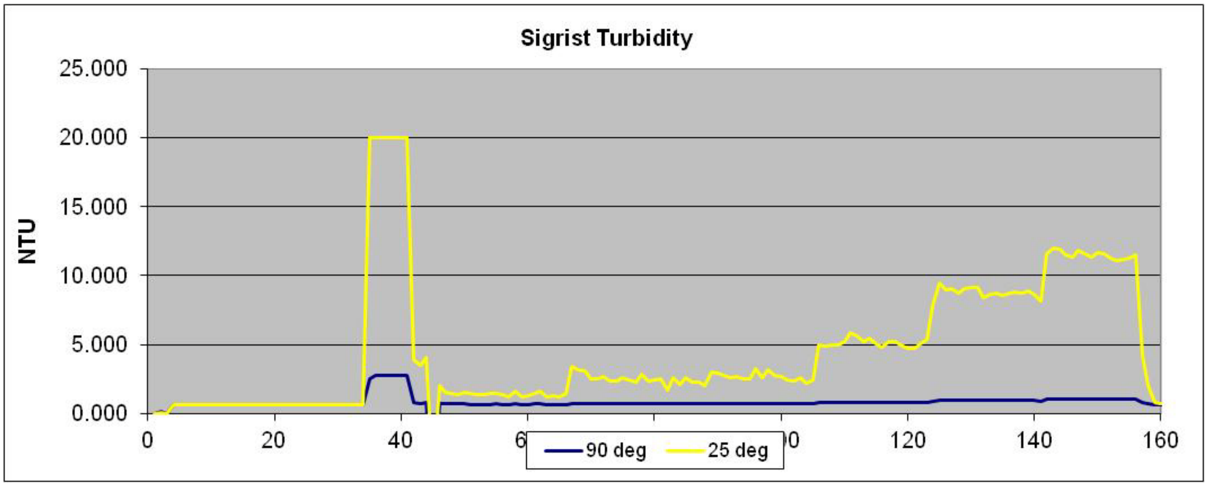



**Figure 26**. Sigrist DualScat Raw Data Challenged with Various Concentrations of Water

Figure 27 illustrates the reversal in signal response with red iron oxide and no water. Figure 28 illustrates the same concentration of ISO 12103-1 A1 ultrafine test dust. The main difference between these two challenges is the color of the solid. The ultrafine test contains mostly quartz, whereas the red iron oxide is red. One could interpret the data from Figure 26 through Figure 28 to conclude that the Sigrist DualScat detects both quartz (clear, translucent) and water in a similar manner, and the colored body RIO differently.

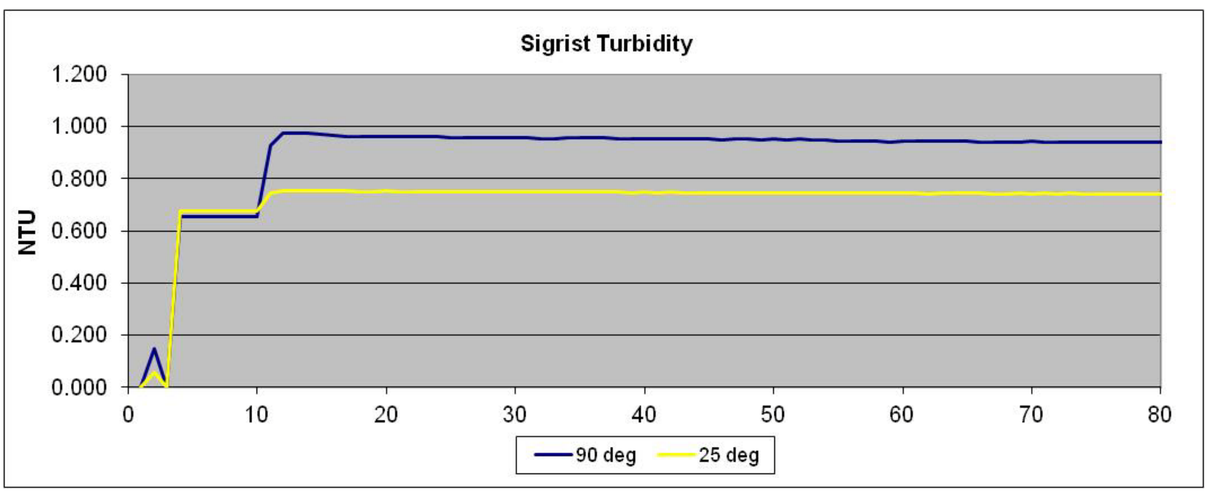



**Figure 27**. Sigrist DualScat Raw Data Challenged with 0.25 mg/L RIO

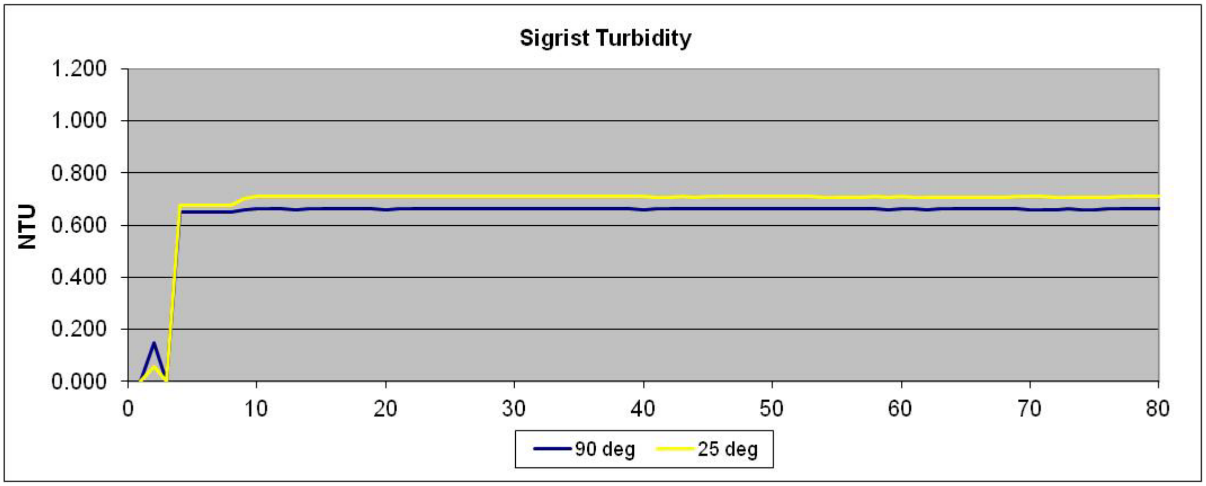



**Figure 28**. Sigrist DualScat Raw Data Challenged with 0.25 mg/L ISO 12103-1 Ultrafine Test Dust

Both the Faudi Jet Guard and Optec TF are only designed to measure water content. Examples of their output using the various water concentration challenges are shown in Figure 29 and Figure 30, respectively. The Faudi Jet Guard calibration requires adjustment as Faudi calibrated this unit with higher water concentrations than is expected in the field. The Optec TF responds to the changes in water content and would be a reasonable technology for determining water contamination issues in the fuel supply system.

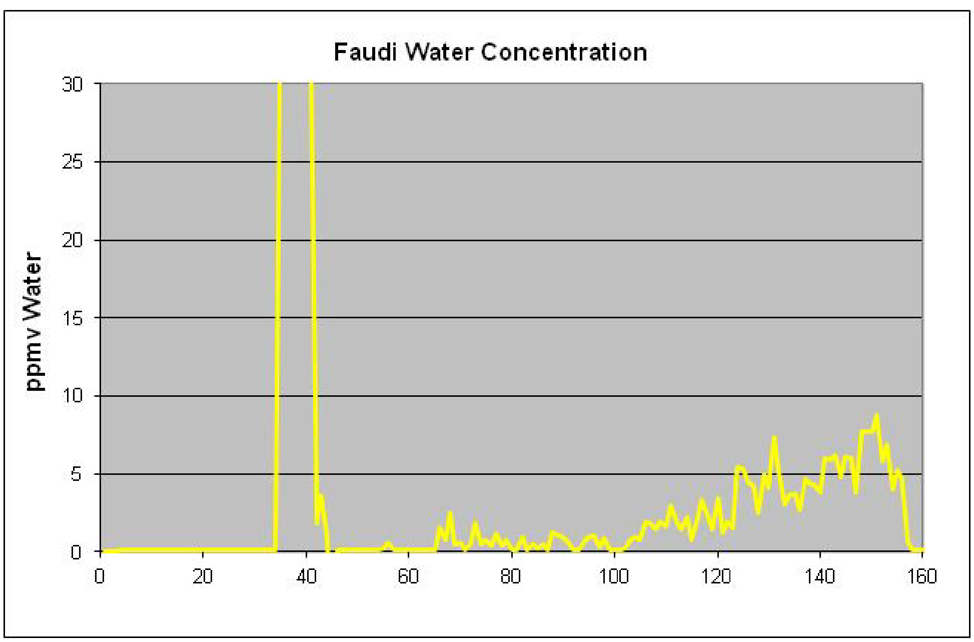



**Figure 29**. Faudi Jet Guard Challenged with Various Concentrations of Water

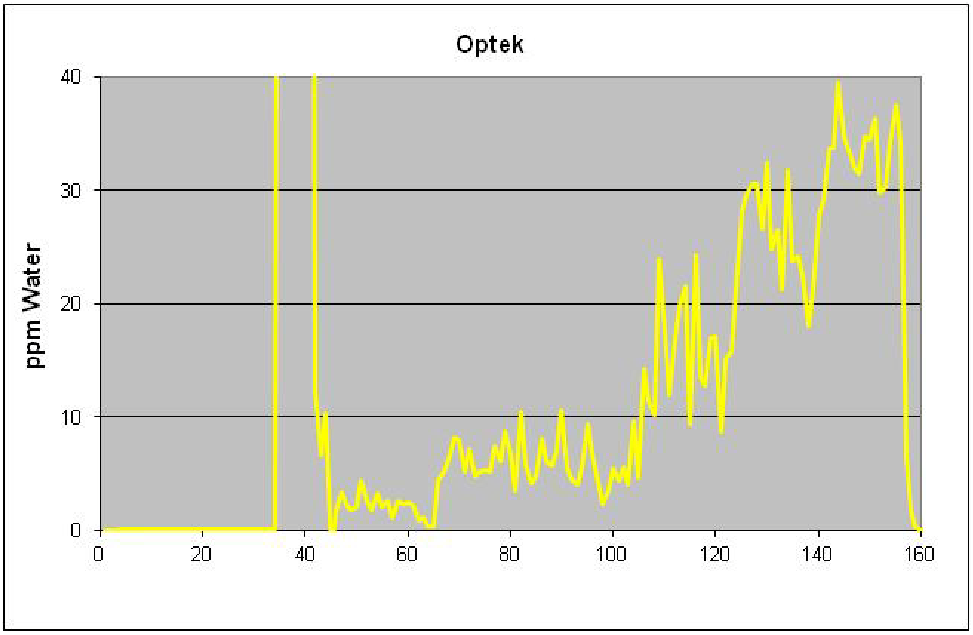



**Figure 30**. Optec TF Challenged with Various Concentrations of Water

## 6.0 CONCLUSIONS

Previous research has shown that sand and dust from various parts of CONUS and OCONUS differ in distribution, morphology, chemical composition, and color. Recent issues with aviation fuel quality has generated the interest in improving fuel quality by obtaining cleanliness online or inline instead of with the traditional gravimetric and Aqua-glo methods. Other industries have used particle counters for determining the cleanliness levels of hydraulic fluid using ISO 4406 as the rating system, and the beer and wine industry has used photometers and turbidimeters for processing their products.

The Energy Institute (EI) published EI 1598 – *Design, functional requirements and laboratory testing protocols for electronic sensors to monitor free water and/or particulate matter in aviation fuel* for qualifying electronic sensors. Using the basic principles of EI 1598, various sensors were evaluated to determine which electronic sensors demonstrate the most promise for detecting water and/or dirt contamination. DEF STAN 91-91 and commercial industries are already recommending or specifying ISO 4406 requirements for fuel cleanliness levels for their applications.

The electronic sensors used for this study included particles counters (light extinction) and photometers and turbitimeters (light scatter). The various instruments were challenged with dusts having different particle size distributions at various concentrations, and having different color. The sensors were also challenged with various concentrations of water with the distributions using the centrifugal pump required in EI 1581.

Particle counter technology (Parker ACM 20 and iCount) was able to properly measure solid particles and provide an indication that excessive water may be present. Particle counter technology cannot provide ppm water results. The photometers/turbitimeters use light scatter technology and demonstrate that this technology is suited for determining water contamination. This research demonstrated that the differing colors of sand dust impact the light scatter results, and thereby the algorithms generated to determine the gravimetric levels.

Based upon the data generated in this report, particle counting technology appears to provide the best electronic sensors to determine the fuel cleanliness levels for dirt and water, and have the fewest false positives. If water is the main issue, photometers or turbitimeters provide a better resource for in-line applications.

## 7.0 REFERENCES


1. Bessee, G.B., and Kohl, K.B., *“Characteristics of CONUS and Saudi Arabian Soil Samples,”* Interim Report BFLRF No. 294, prepared by Belvoir Fuels and Lubricants Research Facility (SwRI), Southwest Research Institute, San Antonio, TX October 1993
2. Bessee, G.B., and Kohl, K.B., *“Comparison Between Real-Life Dust Samples and Standardized Test Dusts”*, SAE Technical Paper 940322, International Congress and Exposition, Detroit, MI, February 28-March 3, 1994

3. Simonis, J.C., Bessee, G.B., Kohl, K.B., and Bequette, L.L., *"Effect of Sand and Fine Debris on Helicopter Systems"*, SwRI Project Number 18-04484, Contract Number OO-CMP-0006, prepared for DESP Contracts Office, OO-ALC/LGKF, Hill AFB, UT 84056-5820 and U.S. Department of the Army, PEO, Aviation, Cargo Helicopter, Redstone Arsenal, AL 35898, August 2003

4. Defence Standard 91-91 Issue 7, Amendment 1, Turbine Fuel, Aviation Kerosene Type, Jet A-1, NATO Code: F-35, JSD: AVTUR

5. International Standard Organization (ISO) 4406:1999(E), Hydraulic Fluid Power – Fluids – Method for coding the level of contamination by solids particles

6. IP423-99, Determination of particulate contaminant in aviation turbine fuels by laboratory filtration

7. ASTM D5452-08, Standard Test Method for Particulate Contamination in Aviation Fuels by Laboratory Filtration

8. International Standard Organization (ISO) 11171:2010(E), Hydraulic Fluid Power – Calibration of automatic particle counters for solids, October 2010

9. National Institute of Standards and Technology (NIST) Certificate of Analysis, Standard Reference Material 2806a, Medium Test Dust (MTD) in Hydraulic Fluid, January 2007

10. Energy Institute 1598 – Design, functional requirements and laboratory testing protocols for electronic sensors to monitor free water and/or particulate matter in aviation fuel, Second Edition, February 2012

11. Bessee, G.B., *"Alternative Fuels Compatibility with Army Equipment Testing – Effects of JP-8+100 on Military Filtration Equipment"*, U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI), San Antonio, TX, for U.S. Army TARDEC Force Projection Technologies, Warren, MI, Contract No. W56HZV-09-C-0100 (WD 15), SwRI Project No. 08.14734.15.300, Interim Report No. 424, February 2012

12. Energy Institute (EI) 1581 – Specifications and Qualification Procedures for Aviation Jet Fuel Filter/Separator, 5th Edition, 2011

# APPENDIX–A: PARKER ACM 20 PARTICLE COUNT RESULTS

**Parker ACM 20 Data – ISO 12103-1 A3 Medium Test Dust**

| Challenge | 0.25 mg/L A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 2.5 | 0.9 | 0.1 | 0.0 | 0.0 | 0.0 |
| 5 | 596.8 | 244.7 | 7.7 | 1.7 | 1.1 | 0.1 |
| 15 | 449.0 | 184.1 | 5.1 | 1.0 | 0.4 | 0.2 |
| 25 | 424.5 | 174.7 | 4.9 | 0.9 | 0.4 | 0.1 |
| 35 | 415.9 | 162.4 | 4.1 | 0.9 | 0.4 | 0.2 |
| 45 | 381.0 | 148.2 | 2.9 | 0.5 | 0.3 | 0.1 |

| Challenge | 0.5 mg/L A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 2.9 | 0.8 | 0.1 | 0.0 | 0.0 | 0.0 |
| 5 | 528.4 | 211.2 | 12.4 | 2.1 | 1.1 | 0.7 |
| 15 | 528.8 | 210.1 | 11.6 | 2.1 | 1.0 | 0.4 |
| 25 | 492.2 | 192.3 | 7.7 | 1.4 | 0.7 | 0.3 |
| 35 | 442.1 | 180.0 | 12.9 | 3.7 | 1.9 | 0.9 |

| Challenge | 1.0 mg/L A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 1.6 | 0.6 | 0.1 | 0.0 | 0.0 | 0.0 |
| 5 | 777.5 | 309.5 | 15.9 | 3.4 | 1.6 | 0.4 |
| 15 | 696.1 | 273.1 | 15.5 | 3.5 | 1.3 | 0.6 |
| 25 | 662.9 | 257.1 | 11.5 | 2.3 | 0.5 | 0.1 |
| 35 | 657.4 | 244.3 | 10.6 | 2.0 | 0.7 | 0.1 |
| 45 | 648.6 | 273.9 | 19.4 | 5.0 | 2.0 | 0.6 |

## Parker ACM 20 Data – ISO 12103-1 A2 Fine Test Dust

| Challenge | 0.25 mg/L A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| **Time, min** | **4** | **6** | **14** | **21** | **25** | **30** |
| 0 | 0.5 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| 5 | 290.1 | 80.1 | 3.2 | 0.7 | 0.4 | 0.1 |
| 15 | 290.1 | 79.7 | 2.4 | 0.6 | 0.2 | 0.1 |
| 25 | 293.1 | 76.5 | 2.3 | 0.6 | 0.3 | 0.1 |
| 35 | 280.1 | 78.0 | 2.3 | 0.6 | 0.0 | 0.0 |
| 45 | 276.4 | 80.1 | 4.1 | 1.1 | 0.9 | 0.2 |

| Challenge | 0.5 mg/L A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| **Time, min** | **4** | **6** | **14** | **21** | **25** | **30** |
| 0 | 2.4 | 0.6 | 0.1 | 0.0 | 0.0 | 0.0 |
| 5 | 582.1 | 166.2 | 6.9 | 1.6 | 0.7 | 0.1 |
| 15 | 560.6 | 156.6 | 5.6 | 1.2 | 0.7 | 0.4 |
| 25 | 532.9 | 149.4 | 4.4 | 1.3 | 0.4 | 0.0 |
| 35 | 435.0 | 124.4 | 5.9 | 1.5 | 0.7 | 0.4 |

| Challenge | 1.0 mg/L A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| **Time, min** | **4** | **6** | **14** | **21** | **25** | **30** |
| 0 | 1.6 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 1175.2 | 325.7 | 11.9 | 2.6 | 1.5 | 0.4 |
| 15 | 1162.1 | 330.9 | 11.7 | 2.4 | 0.9 | 0.4 |
| 25 | 1131.7 | 312.4 | 8.9 | 1.5 | 0.7 | 0.3 |
| 35 | 1058.6 | 287.1 | 8.3 | 1.9 | 0.8 | 0.3 |

Parker ACM 20 Data – ISO 12103-1 A1 Ultra Fine Test Dust

| Challenge | 0.25 mg/L<br>A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 2.4 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 550.8 | 161.9 | 1.9 | 0.2 | 0.1 | 0.1 |
| 15 | 529.1 | 157.2 | 1.1 | 0.1 | 0.1 | 0.1 |
| 25 | 507.8 | 147.1 | 1.0 | 0.0 | 0.0 | 0.0 |
| 35 | 499.8 | 141.3 | 0.5 | 0.0 | 0.0 | 0.0 |

| Challenge | 0.5 mg/L<br>A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 1.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 999.4 | 287.7 | 2.2 | 0.4 | 0.3 | 0.1 |
| 15 | 965.1 | 285.2 | 2.2 | 0.2 | 0.1 | 0.0 |
| 25 | 955.3 | 272.2 | 1.7 | 0.1 | 0.0 | 0.0 |
| 35 | 907.4 | 256.1 | 1.1 | 0.0 | 0.0 | 0.0 |

| Challenge | 1.0 mg/L<br>A3 Test Dust | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 1.9 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 2040.6 | 609.2 | 4.3 | 0.4 | 0.0 | 0.0 |
| 15 | 2053.1 | 593.6 | 3.4 | 0.1 | 0.0 | 0.0 |
| 25 | 1970.7 | 568.4 | 3.6 | 0.2 | 0.0 | 0.0 |
| 35 | 1934.9 | 548.1 | 3.3 | 0.1 | 0.0 | 0.0 |

## Parker ACM 20 Data – Red Iron Oxide Test Dust

| Challenge | 0.25 mg/L RIO | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 3.6 | 2.0 | 0.1 | 0.0 | 0.0 | 0.0 |
| 5 | 1715.9 | 225.6 | 0.6 | 0.0 | 0.0 | 0.0 |
| 15 | 1708.4 | 240.6 | 1.1 | 0.0 | 0.0 | 0.0 |
| 25 | 1729.1 | 246.5 | 1.1 | 0.1 | 0.0 | 0.0 |
| 35 | 1727.1 | 240.9 | 1.1 | 0.2 | 0.2 | 0.0 |

| Challenge | 0.5 mg/L RIO | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 3.1 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 3214.2 | 425.7 | 1.6 | 0.1 | 0.0 | 0.0 |
| 15 | 3256.1 | 450.6 | 0.3 | 0.3 | 0.0 | 0.0 |
| 25 | 3291.6 | 490.7 | 1.9 | 0.1 | 0.0 | 0.0 |
| 35 | 3048.6 | 422.7 | 1.5 | 1.0 | 0.0 | 0.0 |

| Challenge | 1.0 mg/L RIO | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| Time, min | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 4.1 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 7124.9 | 1083.6 | 4.1 | 0.3 | 0.2 | 0.0 |
| 15 | 7176.0 | 1118.1 | 2.8 | 0.0 | 0.0 | 0.0 |
| 25 | 7224.5 | 1141.6 | 3.0 | 0.2 | 0.0 | 0.0 |
| 35 | 7196.6 | 1153.2 | 2.6 | 0.1 | 0.0 | 0.0 |

| Challenge | 0.25 mg/L<br>RIO<br>2 ppm Water | | | | | |
|---|---|---|---|---|---|---|
| | ACM 20 | | | | | |
| | Particle Size | | | | | |
| **Time, min** | **4** | **6** | **14** | **21** | **25** | **30** |
| 0 | 11.5 | 7.6 | 0.5 | 0.1 | 0.1 | 0.1 |
| 5 | 6134.2 | 3407.4 | 385.7 | 89.1 | 29.5 | 5.9 |
| 15 | 4526.8 | 2222.2 | 230.3 | 52.4 | 18.0 | 3.1 |
| 25 | 4078.6 | 1923.7 | 191.4 | 42.4 | 14.7 | 3.1 |
| 30 | 4000.1 | 1812.6 | 180.1 | 41.1 | 14.6 | 2.9 |

# APPENDIX–B: PARKER ICOUNT PARTICLE COUNT RESULTS

**Parker iCount Data – ISO 12103-1 A3 Medium Test Dust**

| Challenge | 0.25 mg/L A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| Time, min | 4 | 6 | 14 |
| 0 | 15 | 10 | 0 |
| 5 | 15 | 9 | 0 |
| 15 | 15 | 9 | 0 |
| 25 | 15 | 10 | 0 |
| 35 | 15 | 9 | 0 |
| 45 | 15 | 10.0 | 7.0 |

| Challenge | 0.5 mg/L A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| Time, min | 4 | 6 | 14 |
| 0 | 11 | 0 | 0 |
| 5 | 16 | 10 | 0 |
| 15 | 16 | 10 | 0 |
| 25 | 16 | 10 | 0 |
| 35 | 16 | 10 | 0 |
| 45 | 16 | 10 | 0 |

| Challenge | 1.0 mg/L A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| Time, min | 4 | 6 | 14 |
| 0 | 10 | 0 | 0 |
| 5 | 17 | 11 | 0 |
| 15 | 17 | 11 | 7 |
| 25 | 17 | 11 | 7 |
| 35 | 17 | 11 | 0 |
| 45 | 17 | 11 | 0 |

## Parker iCount Data – ISO 12103-1 A2 Fine Test Dust

| Challenge | 0.25 mg/L<br>A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 8 | 0 | 0 |
| 5 | 15 | 8 | 0 |
| 15 | 15 | 0 | 0 |
| 25 | 15 | 9 | 0 |
| 35 | 15 | 9 | 0 |
| 45 | 15 | 9 | 0 |

| Challenge | 0.5 mg/L<br>A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 7 | 0 | 0 |
| 5 | 17 | 10 | 0 |
| 15 | 16 | 10 | 0 |
| 25 | 16 | 11 | 0 |
| 35 | 16 | 10 | 0 |
| 45 | 16 | 9 | 0 |

| Challenge | 1.0 mg/L<br>A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 7 | 0 | 0 |
| 5 | 18 | 10 | 0 |
| 15 | 18 | 12 | 7 |
| 25 | 17 | 10 | 0 |
| 35 | 17 | 11 | 7 |
| 45 | 17 | 11 | 0 |

**Parker iCount Data – ISO 12103-1 A1 Ultra Fine Test Dust**

| Challenge | 0.25 mg/L<br>A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 7 | 0 | 0 |
| 5 | 16 | 7 | 0 |
| 15 | 17 | 7 | 0 |
| 25 | 16 | 7 | 0 |
| 35 | 16 | 0 | 0 |
| 45 | 16 | 8 | 0 |

| Challenge | 0.5 mg/L<br>A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 0 | 0 | 0 |
| 5 | 10 | 0 | 0 |
| 15 | 17 | 9 | 0 |
| 25 | 17 | 7 | 0 |
| 35 | 17 | 8 | 0 |
| 45 | 17 | 7 | 0 |

| Challenge | 1.0 mg/L<br>A3 Test Dust | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | 4 | 6 | 14 |
| 0 | 0 | 0 | 0 |
| 5 | 18 | 7 | 0 |
| 15 | 18 | 0 | 0 |
| 25 | 18 | 9 | 0 |
| 35 | 18 | 7 | 0 |
| 45 | 18 | 7 | 0 |

**Parker iCount Data –Red Iron Oxide (RIO)**

| Challenge | 0.25 mg/L RIO | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 9 | 0 | 0 |
| 5 | 10 | 0 | 0 |
| 15 | 17 | 0 | 0 |
| 25 | 17 | 0 | 0 |
| 35 | 17 | 0 | 0 |
| 45 | 17 | 8 | 0 |

| Challenge | 0.5 mg/L RIO | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 7 | 0 | 0 |
| 5 | 18 | 8 | 0 |
| 15 | 18 | 0 | 0 |
| 25 | 18 | 0 | 0 |
| 35 | 18 | 0 | 0 |
| 45 | 18 | 7 | 0 |

| Challenge | 1.0 mg/L RIO | | |
|---|---|---|---|
| | iCount | | |
| | ISO 4406 | | |
| **Time, min** | **4** | **6** | **14** |
| 0 | 7 | 0 | 0 |
| 5 | 8 | 0 | 0 |
| 15 | 19 | 0 | 0 |
| 25 | 19 | 7 | 7 |
| 35 | 19 | 7 | 0 |
| 45 | 19 | 9 | 0 |

# APPENDIX–C: WATER PARTICLE COUNT RESULTS

### 1.5 ppm Water

| Time | Particle Size, µm (c) | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 6 | 14 | 21 | 25 | 30 |
| 0.0 | 5.1 | 1.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| 10.0 | 3155.5 | 2121.1 | 230.5 | 54.9 | 18.4 | 3.1 |
| 15.0 | 2826.9 | 1896.9 | 212.6 | 48.1 | 16.1 | 3.2 |
| Ave | 2991.2 | 2009.0 | 221.6 | 51.5 | 17.3 | 3.2 |

### 4 ppm Water

| Time | Particle Size, µm (c) | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 6 | 14 | 21 | 25 | 30 |
| 0.0 | 7.3 | 2.2 | 0 | 0 | 0 | 0 |
| 5.0 | 7568.4 | 5147.6 | 603.4 | 138.8 | 43.9 | 7.9 |
| 10.0 | 6867.6 | 4672.9 | 564.1 | 129.1 | 44.7 | 10.1 |
| Ave | 7218.0 | 4910.3 | 583.8 | 134.0 | 44.3 | 9.0 |

### 5 ppm Water

| Time | Particle Size, µm (c) | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 9.4 | 3.1 | 0.4 | 0 | 0 | 0 |
| 5.0 | 8081.4 | 5490.6 | 659.0 | 152.9 | 49.9 | 9.5 |
| 10.0 | 7184.9 | 4901.9 | 588.8 | 135.1 | 45.1 | 9.1 |
| Ave | 7633.2 | 5196.3 | 623.9 | 144.0 | 47.5 | 9.3 |

**15 ppm Water**

| Time | Particle Size, µm (c) | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 5.1 | 1.1 | 0.1 | 0 | 0 | 0 |
| 5.0 | 17725.3 | 12356.0 | 1679.9 | 398.3 | 135.8 | 25.1 |
| 10.0 | 16542.3 | 11578.4 | 1594.6 | 379.1 | 133.0 | 28.6 |
| Ave | 17133.8 | 11967.2 | 1637.3 | 388.7 | 134.4 | 26.9 |

**25 ppm Water**

| Time | Particle Size, µm (c) | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 8.8 | 2.1 | 0.2 | 0 | 0 | 0 |
| 5.0 | 26820.8 | 19179.0 | 3066.4 | 748.6 | 269.6 | 56.8 |
| 10.0 | 25755.6 | 18467.8 | 2988.5 | 745.8 | 267.9 | 57.9 |
| Ave | 26288.2 | 18823.4 | 3027.5 | 747.2 | 268.8 | 57.4 |

**40 ppm Water**

| Time | Particle Size, µm (c) | | | | | |
|---|---|---|---|---|---|---|
| | 4 | 6 | 14 | 21 | 25 | 30 |
| 0 | 4.6 | 1.1 | 0 | 0 | 0 | 0 |
| 5.0 | 32746.4 | 23782.5 | 4227.9 | 1075.7 | 394.6 | 85.1 |
| 10.0 | 31432.5 | 22889.7 | 4102.6 | 1047.6 | 384.2 | 81.9 |
| Ave | 32089.5 | 23336.1 | 4165.3 | 1061.7 | 389.4 | 83.5 |

# APPENDIX–D: VCA CV02

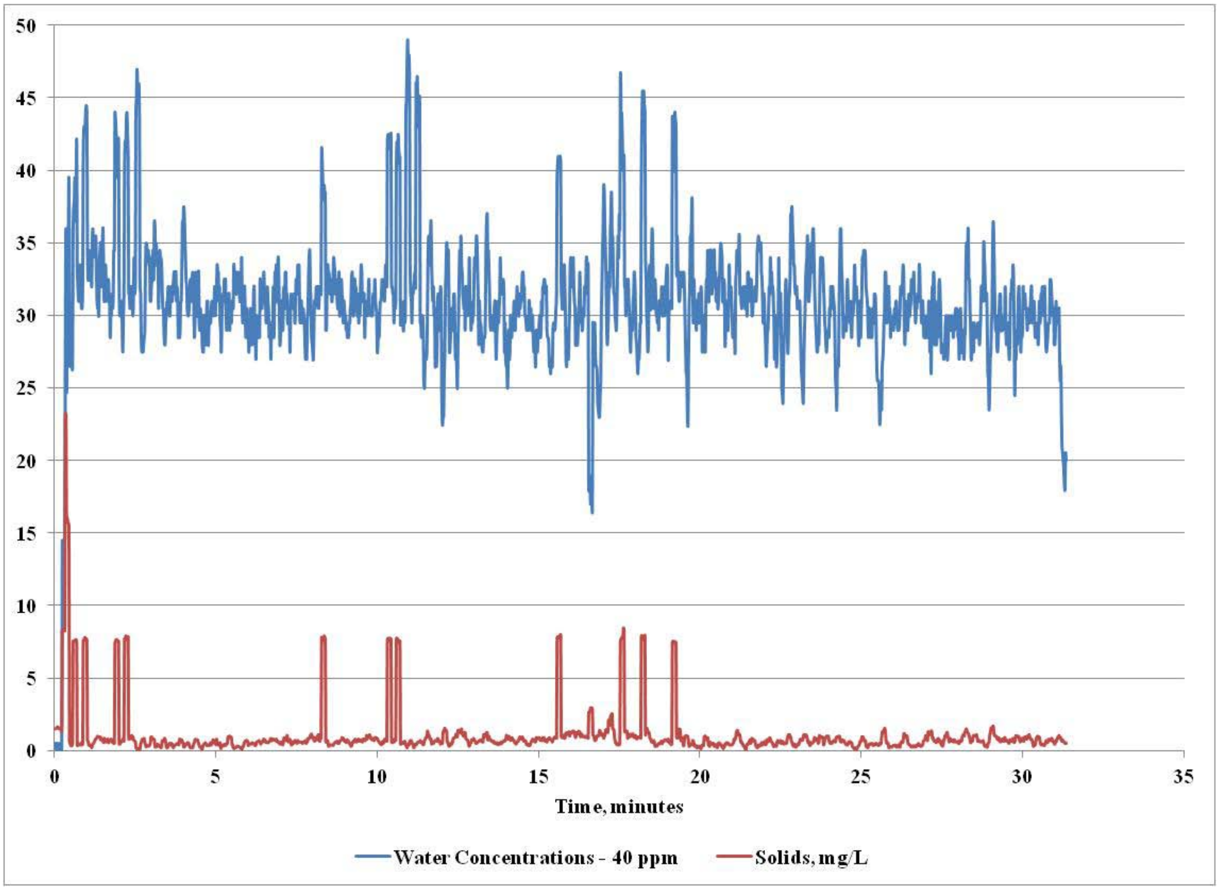



**Figure D-1. Water Challenge – 40 ppm; No Solids**

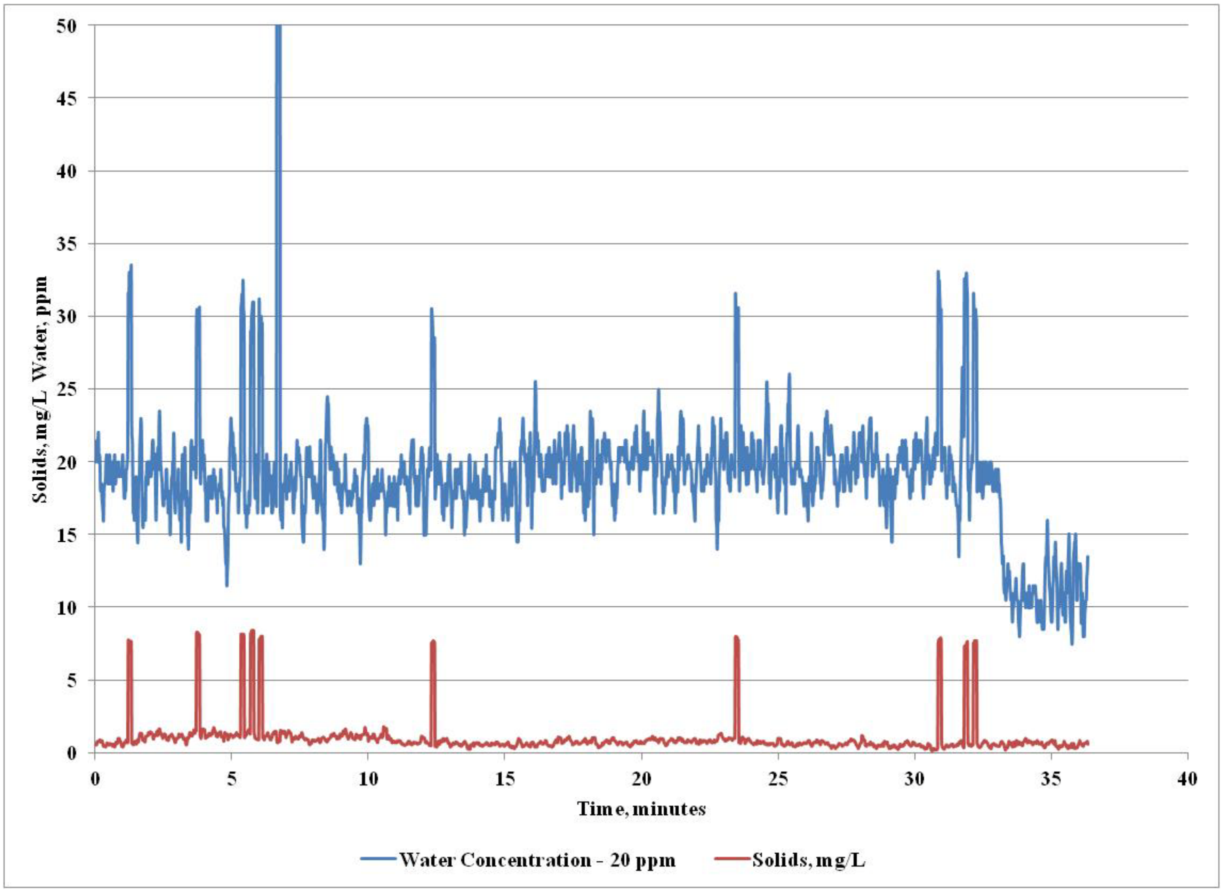



**Figure D-2. Water Challenge – 20 ppm; No Solids**

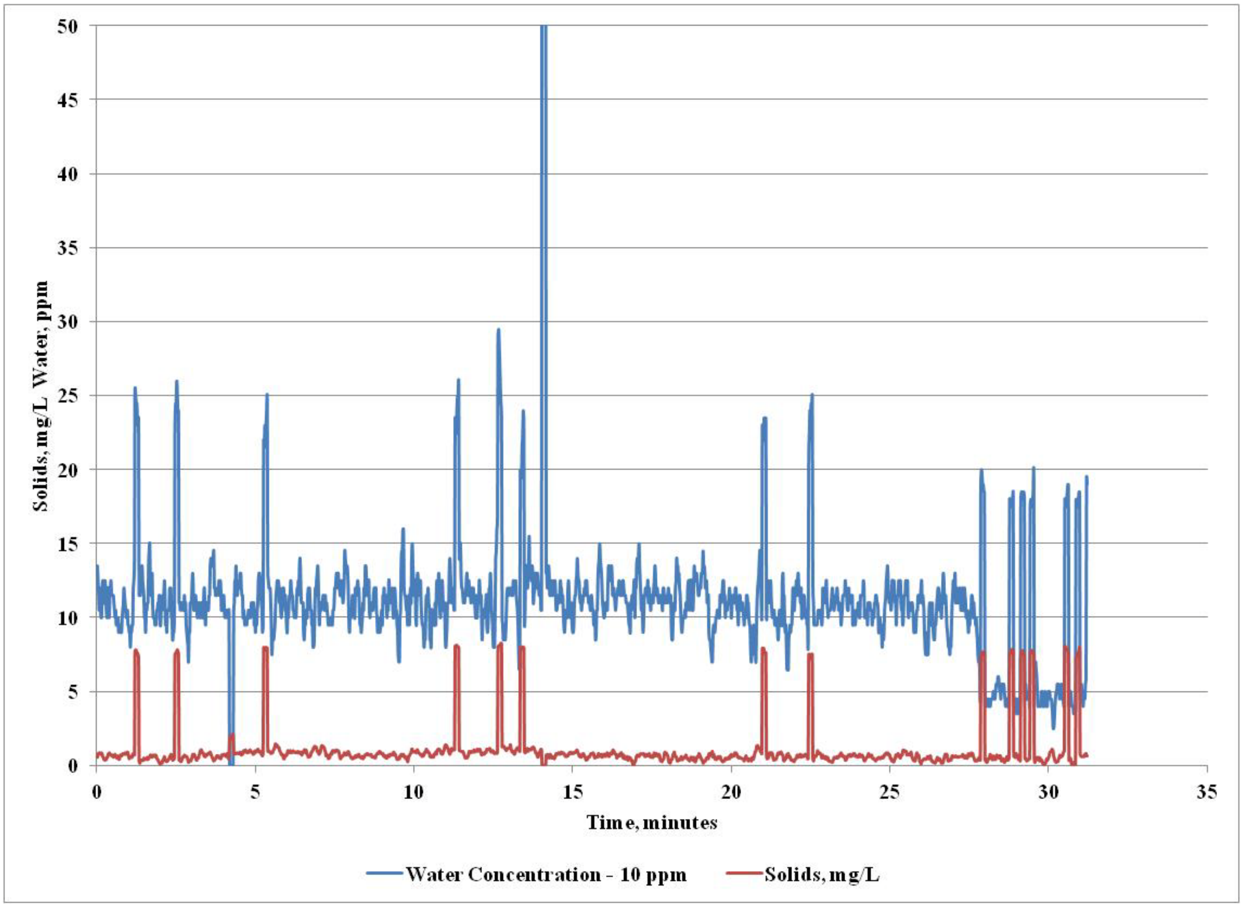



**Figure D-3. Water Challenge – 10 ppm; No Solids**

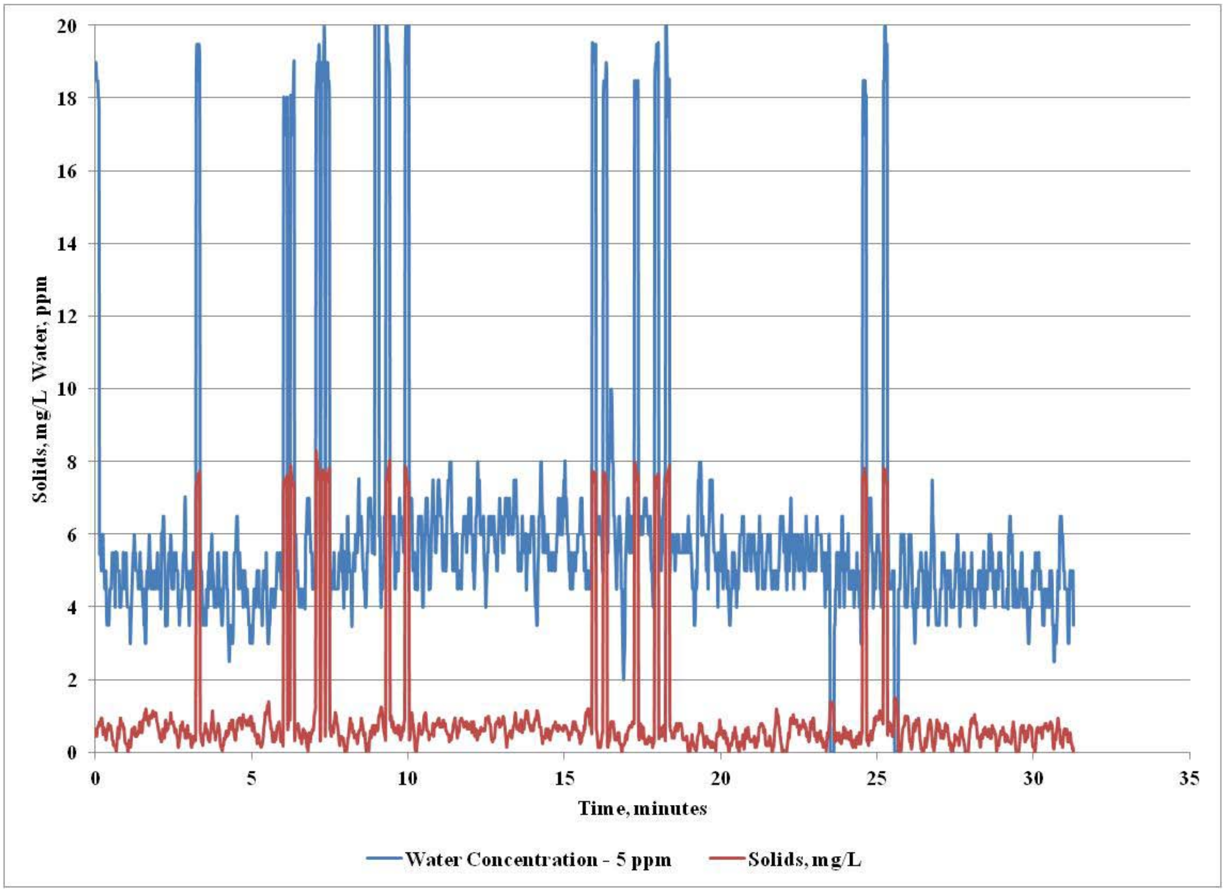



**Figure D-4. Water Challenge – 5 ppm; No Solids**

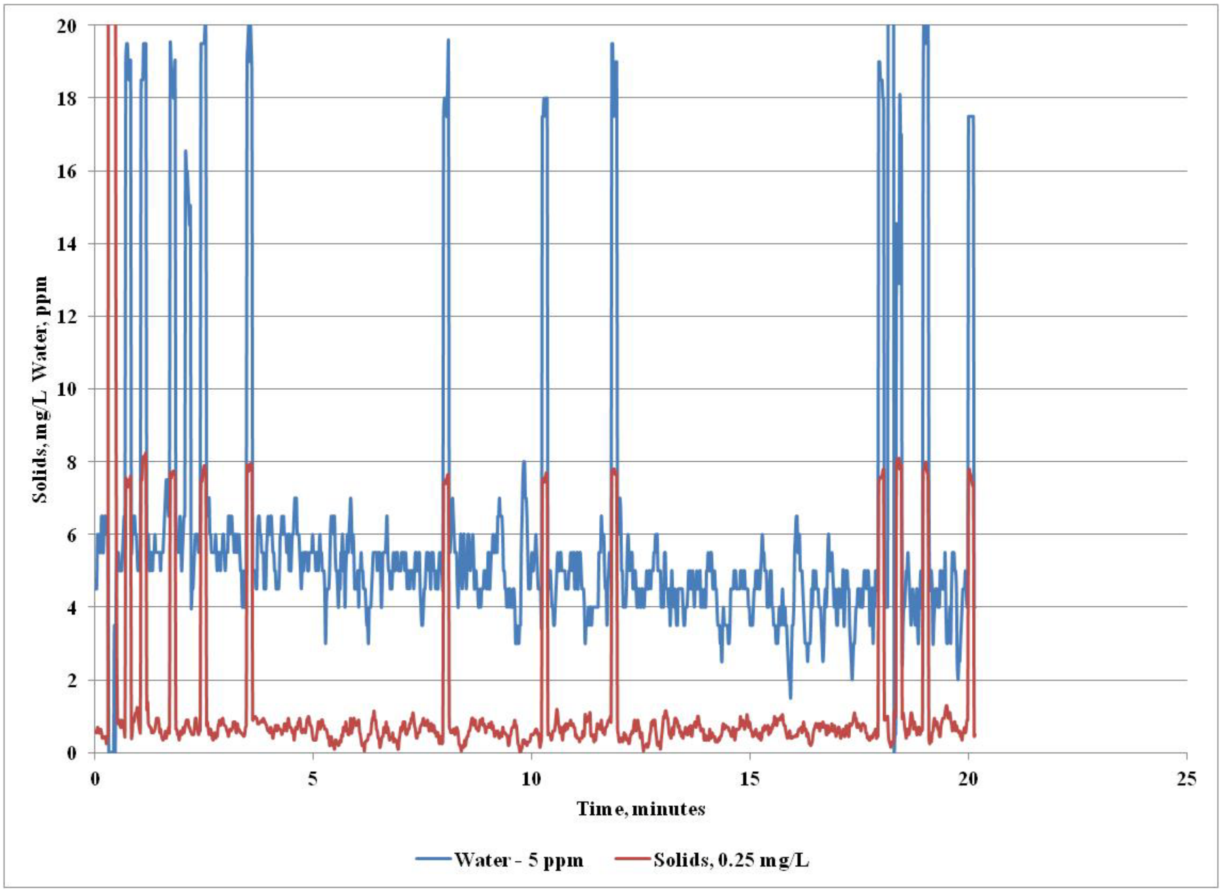



**Figure D-5. VCA-CV02 Challenged with 5 ppm Water and 0.25 mg/L RIO**